νA Interactions

The 22nd FPCP conference, Bangkok, Thailand

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Neutrino Physics

The Neutrino sector might hint to physics beyond the Standard Model

ν_e ν_μ ν_τ

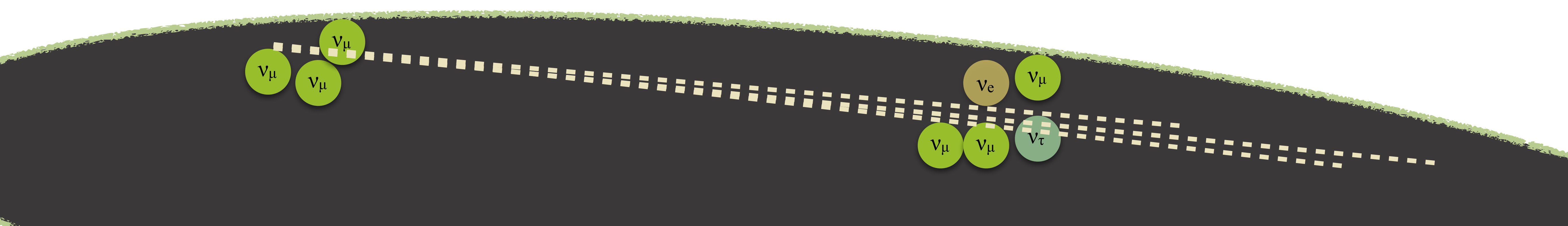
Neutrino oscillate from one flavour to another

Implying their mass and imposing many questions:

What is their mass ordering?

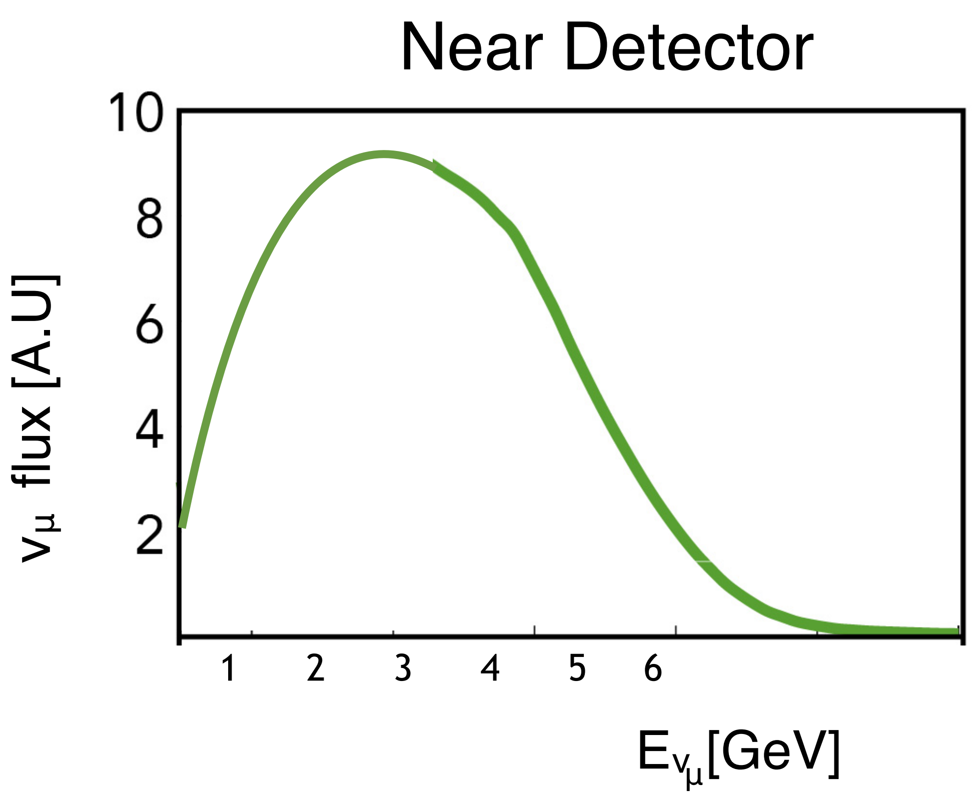
Is CP symmetry violated?

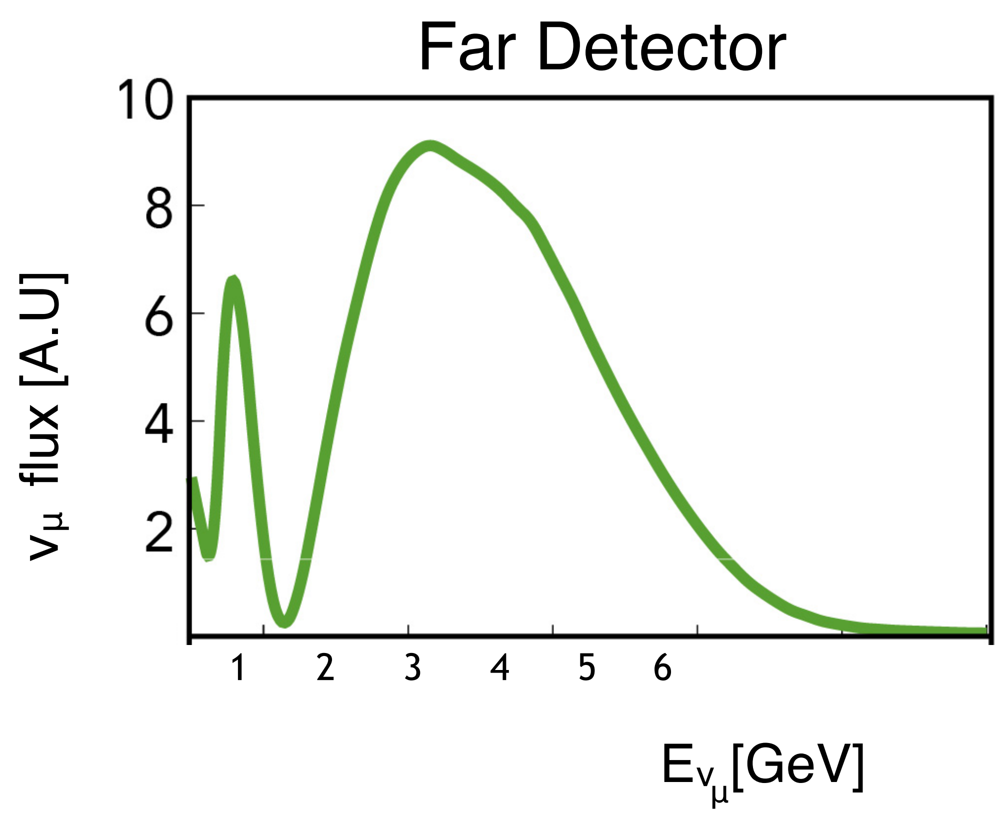
Are there more than the 3 light neutrinos?

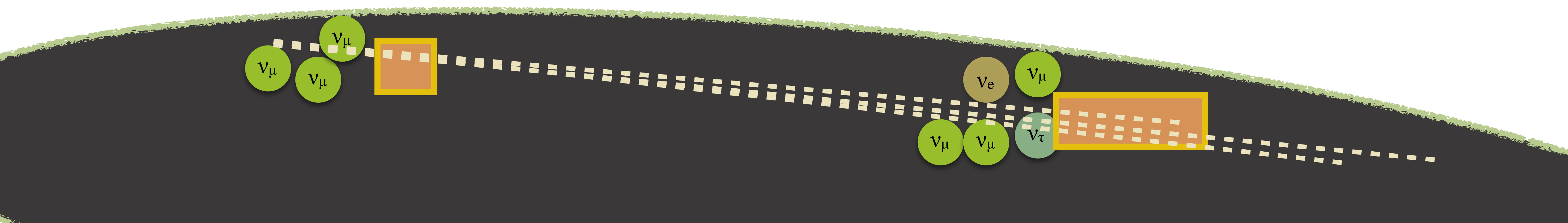


The challenge - next generation high precision

Oscillation experiments aim to answer the CP nature and the mass ordering of neutrinos as well as search for new physics



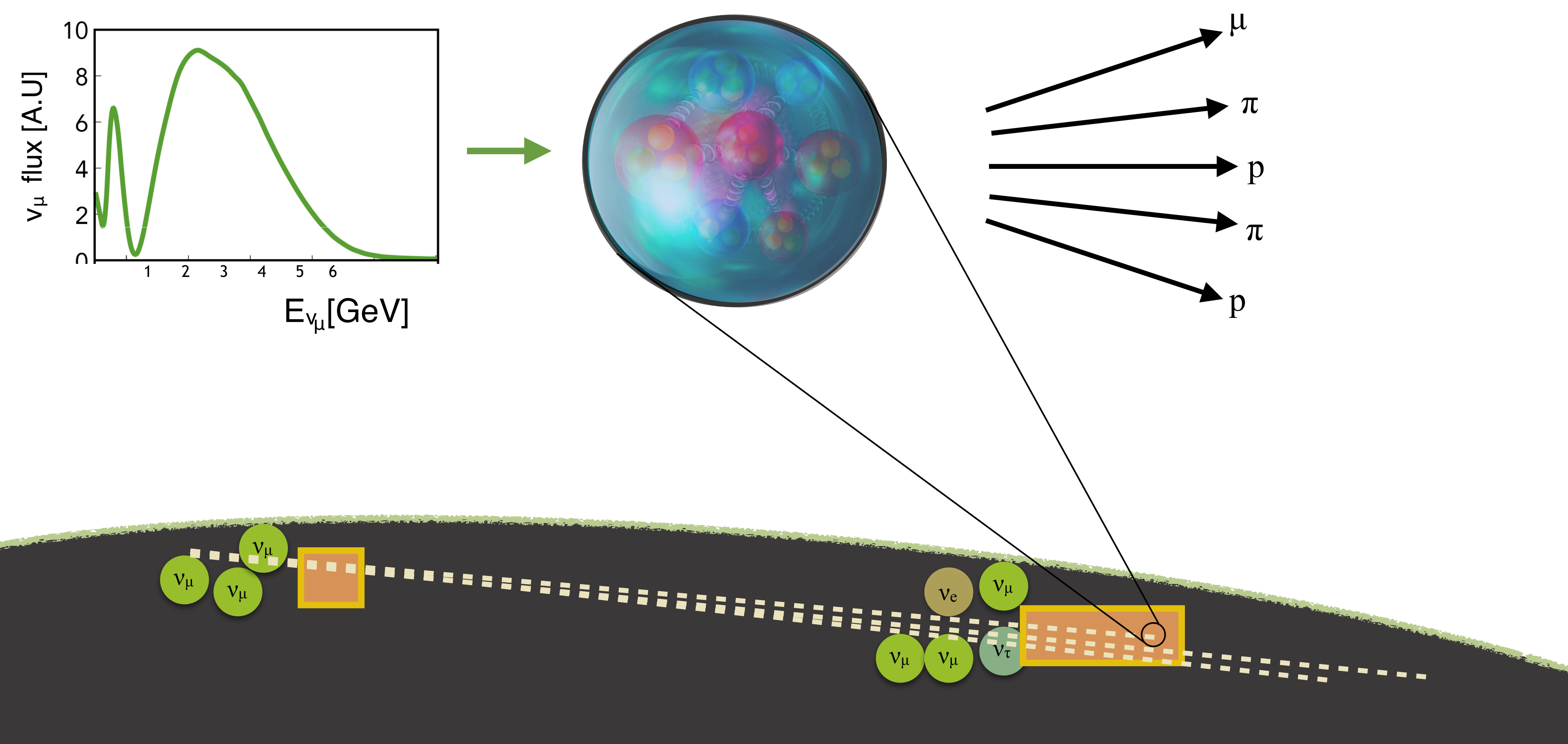




The challenge - next generation high precision

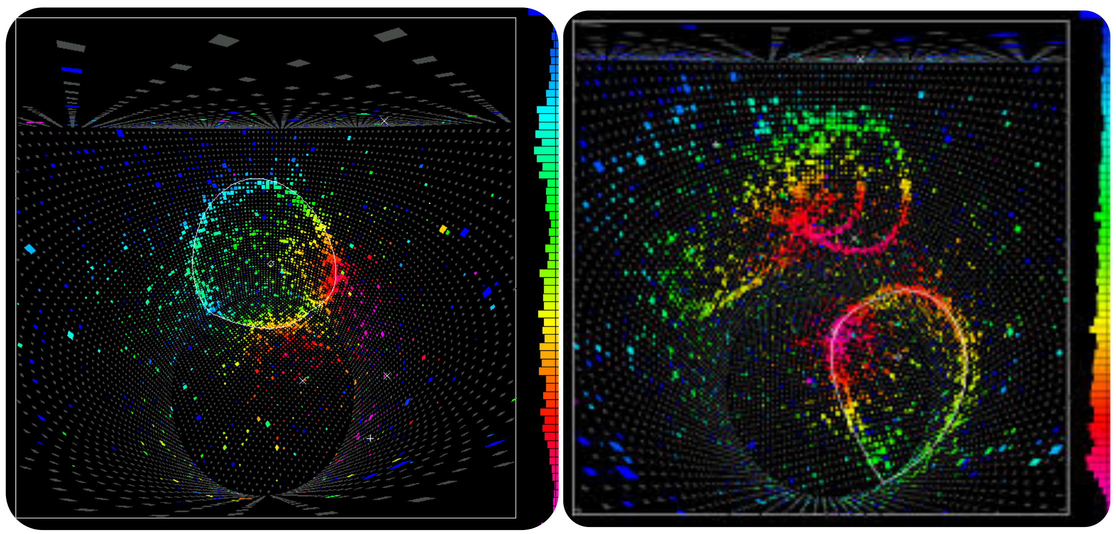
Incoming true flux — Modelling Input — Measurement

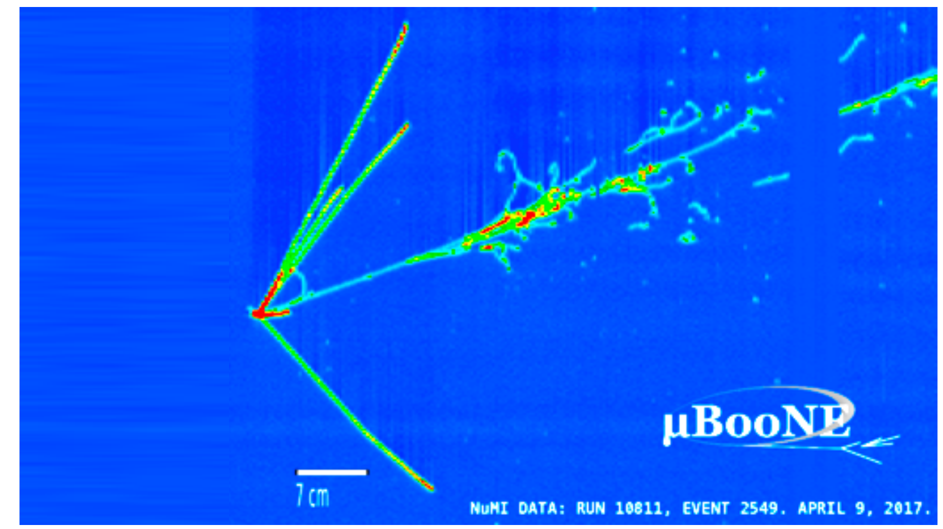
$$\int \Phi(E,L) \quad \sigma(E) f_\sigma(E,E_{rec})\, dE \quad \propto \quad N(E_{rec},L)$$



Incoming Energy Reconstruction

QE-like events





Cherenkov detectors:

Assuming QE interaction

Using lepton only

$$E_{QE} = \frac{2M\epsilon + 2ME_l - m_l^2}{2(M - E_l + |k_l|\cos\theta_l)}$$

Tracking detectors:

Calorimetric sum

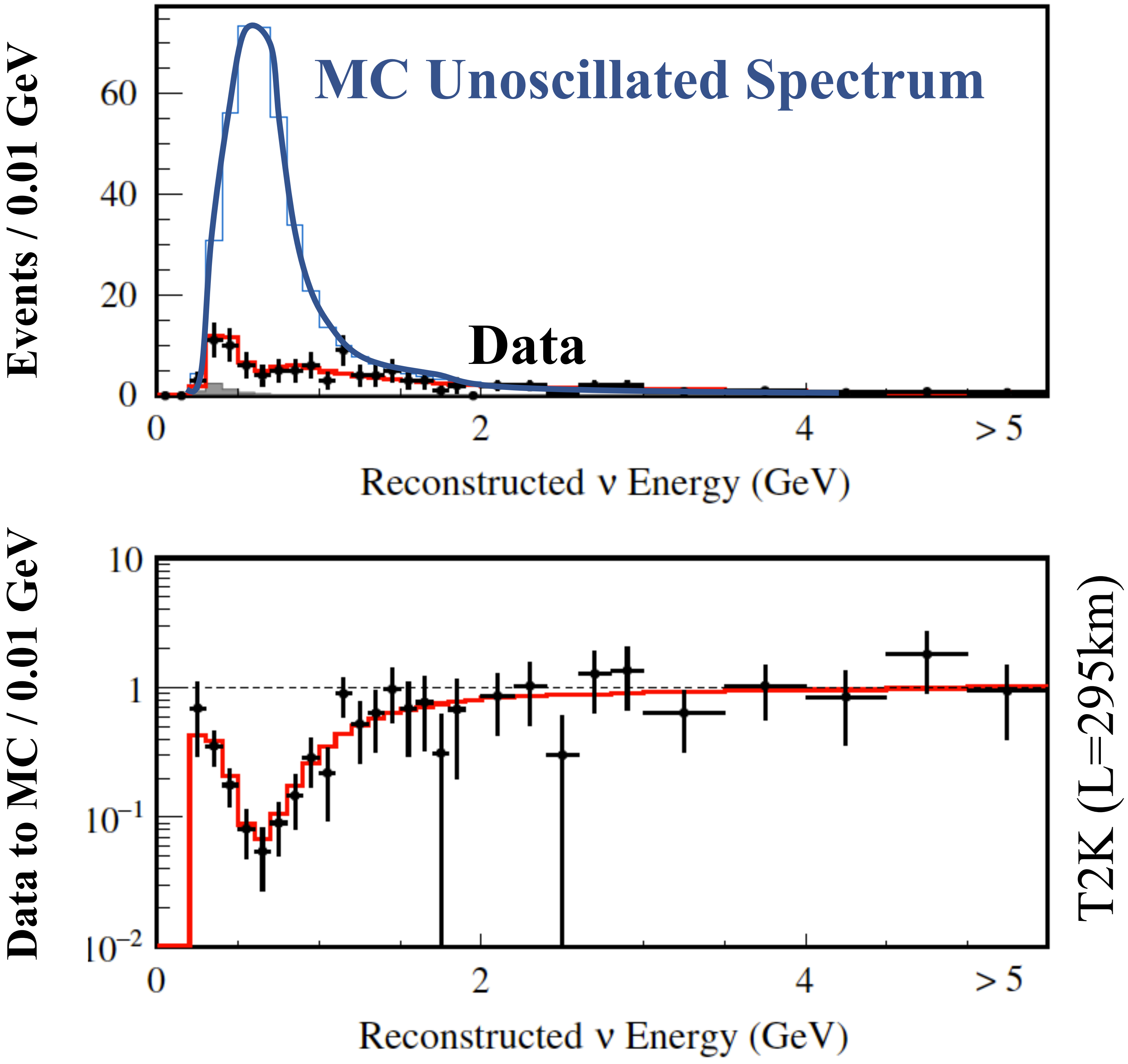
Using All detected particles

$$E_{\text{cal}} = E_l + E_p^{\text{kin}} + \epsilon$$

[1p0π]

ϵ is the nucleon separation energy ~ 20 MeV

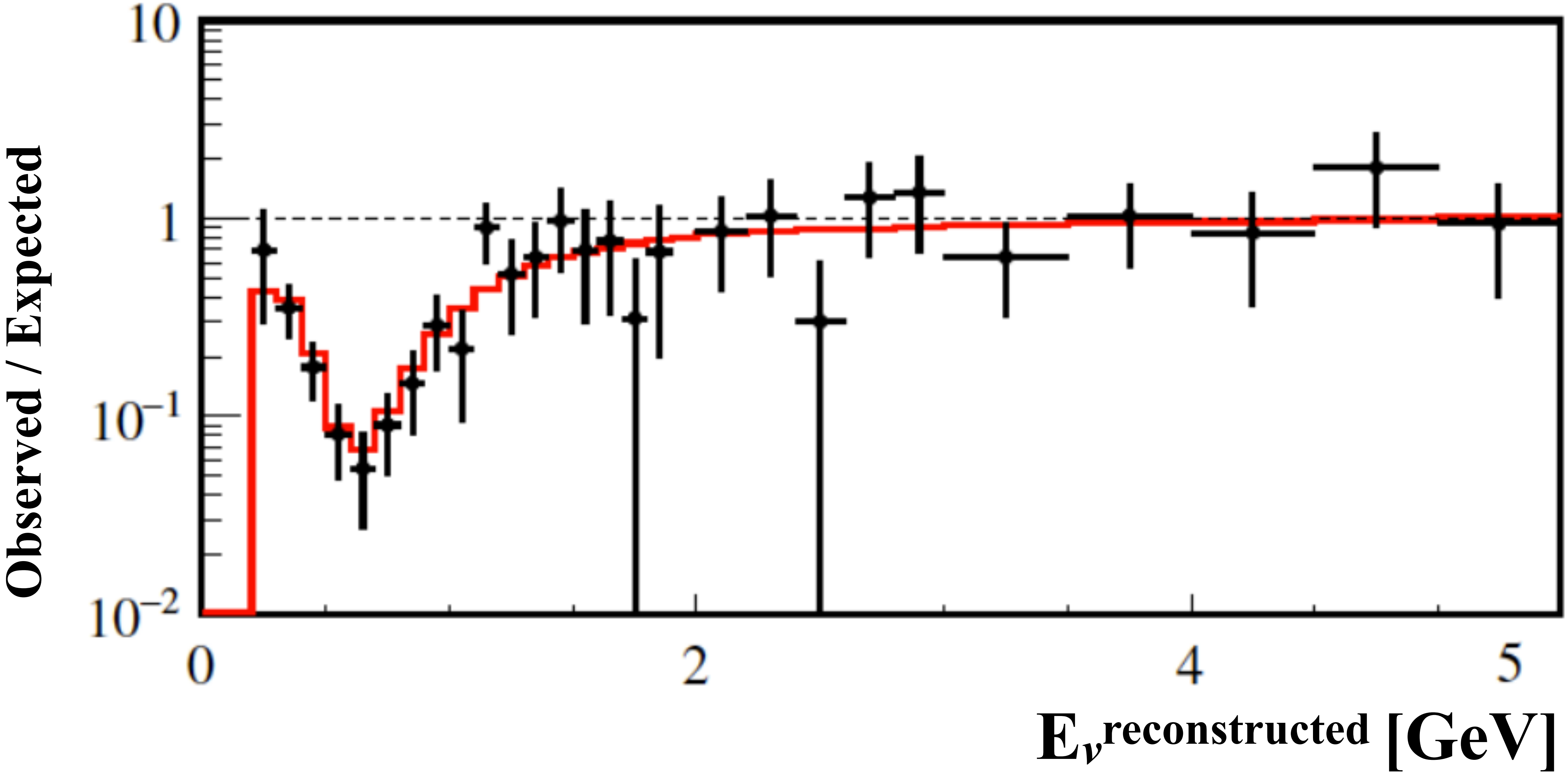
Oscillations Require incoming E_ν Reconstruction



T2K, Phys. Rev. D 91, 072010 (2015)

Oscillations Require incoming E_ν Reconstruction

$$P(\nu_\mu \to \nu_x) = \sin^2(2\theta) \times \sin^2\left(\frac{\Delta m^2 L}{4E_\nu}\right)$$



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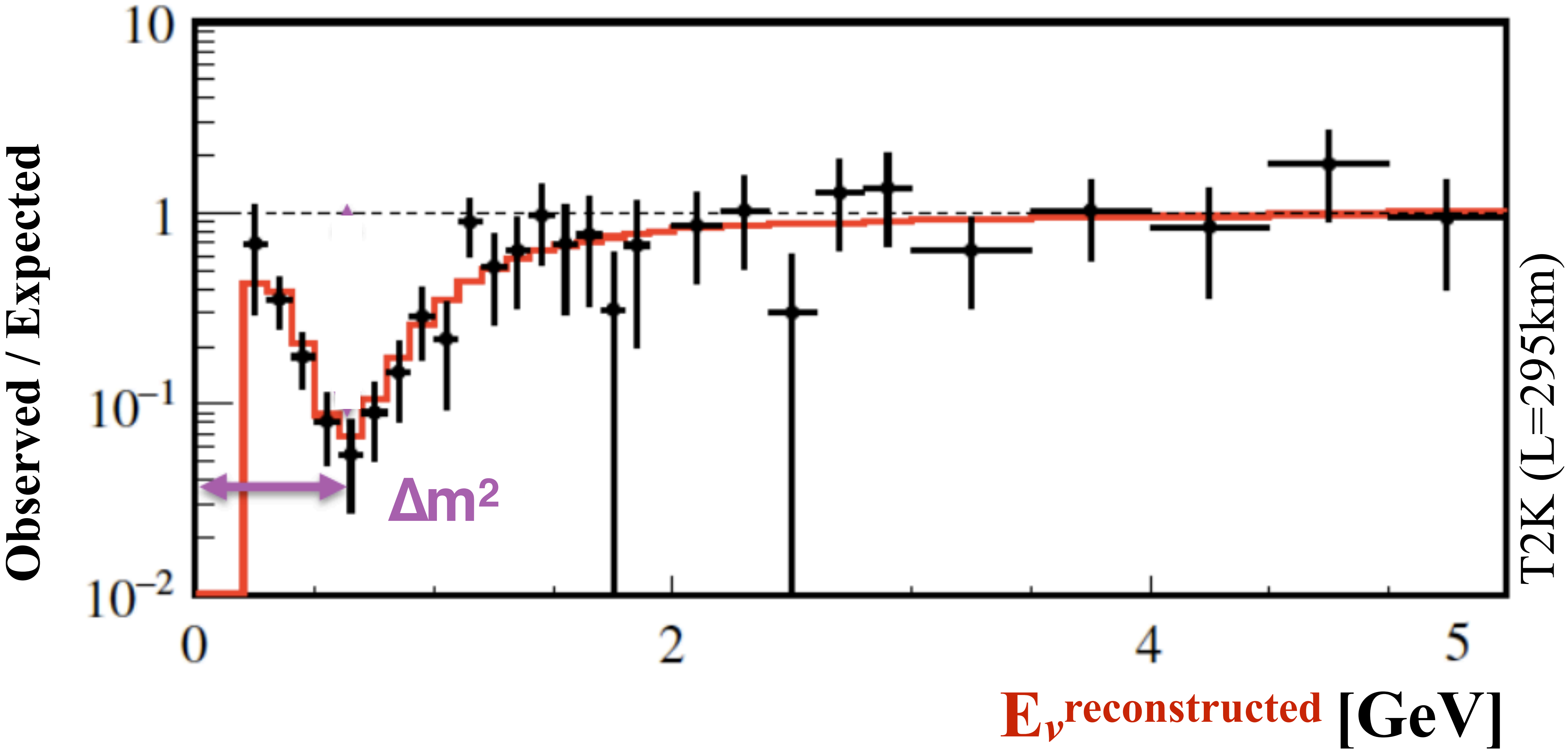
Oscillations Require incoming E_ν Reconstruction

$$P(\nu_\mu \rightarrow \nu_x) = \sin^2(2\theta) \times \sin^2\left(\frac{\Delta m^2 L}{4E_\nu^{true}}\right)$$



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Oscillations Require incoming E_ν Reconstruction

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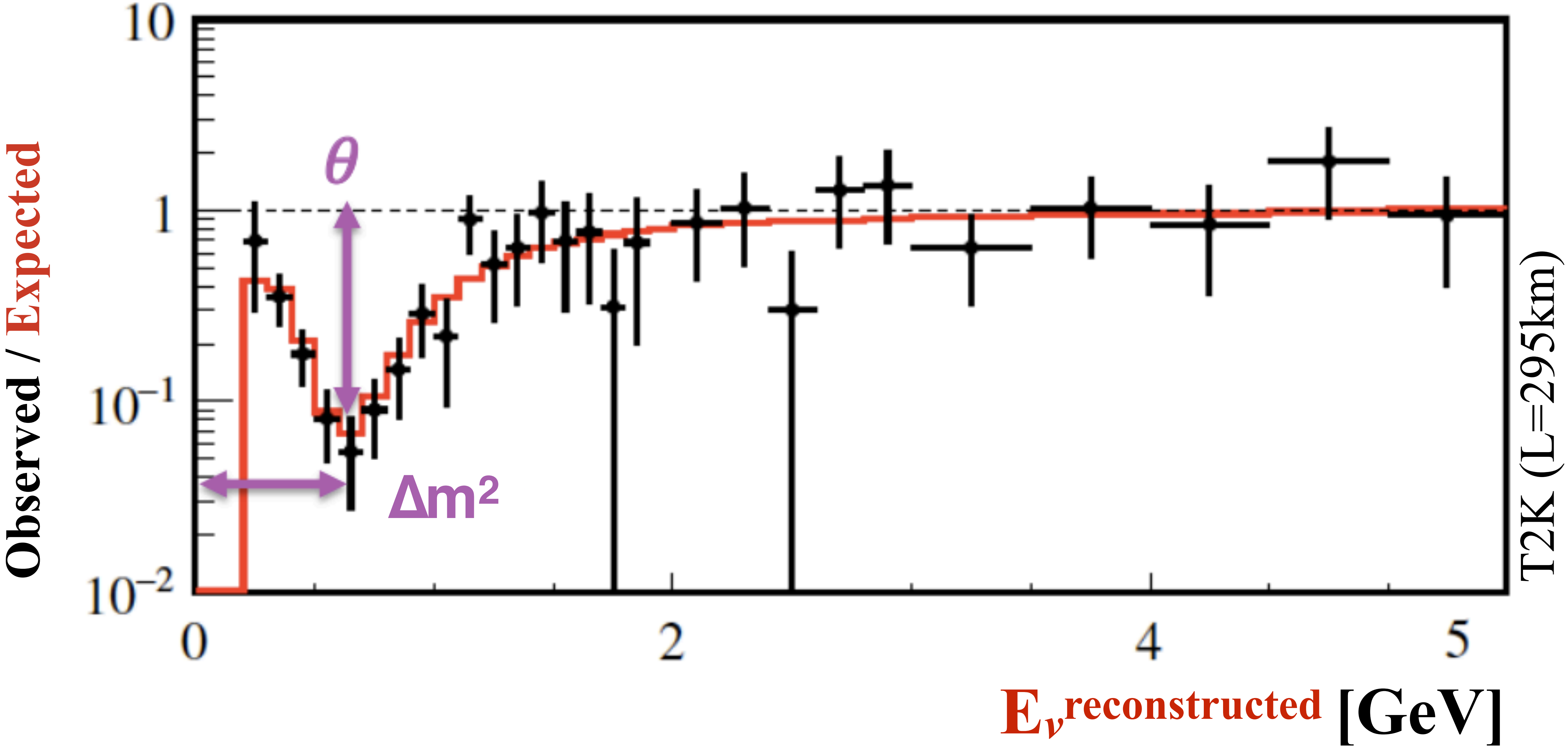

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The challenge - next generation high precision

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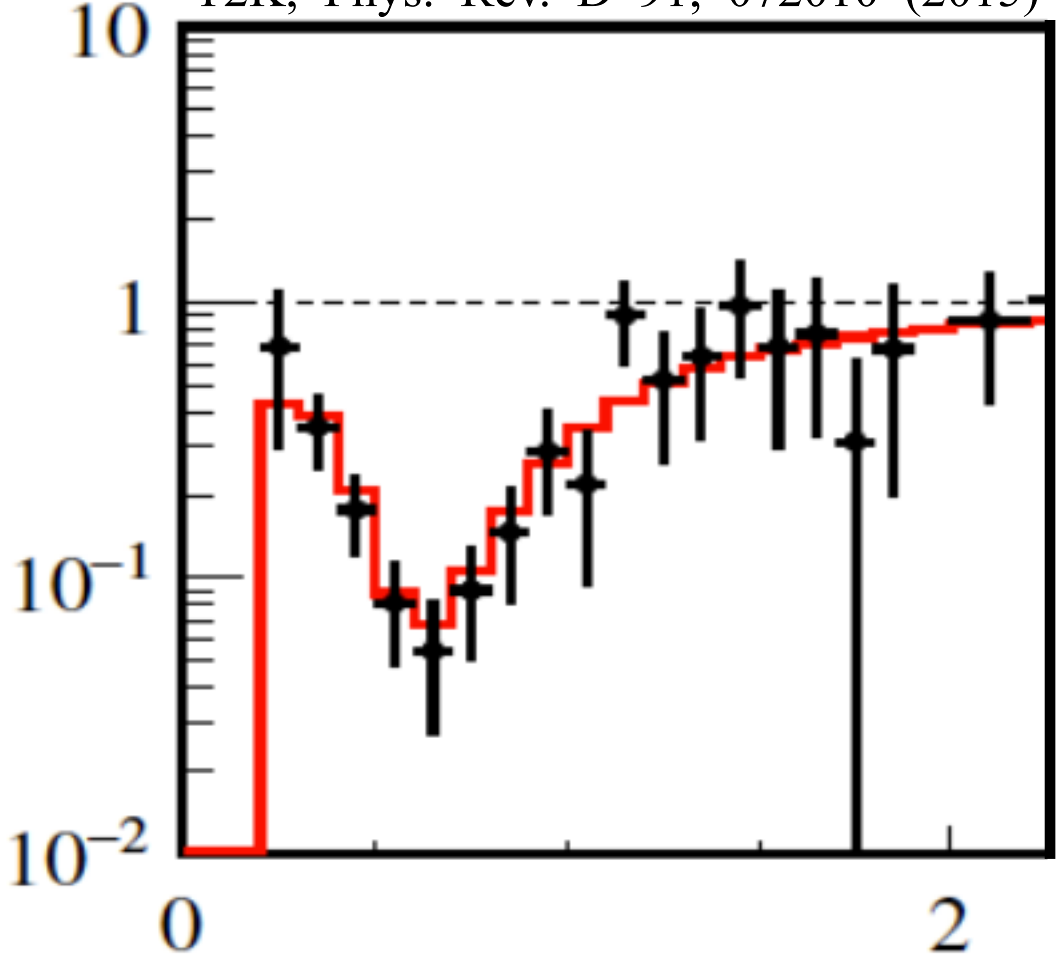
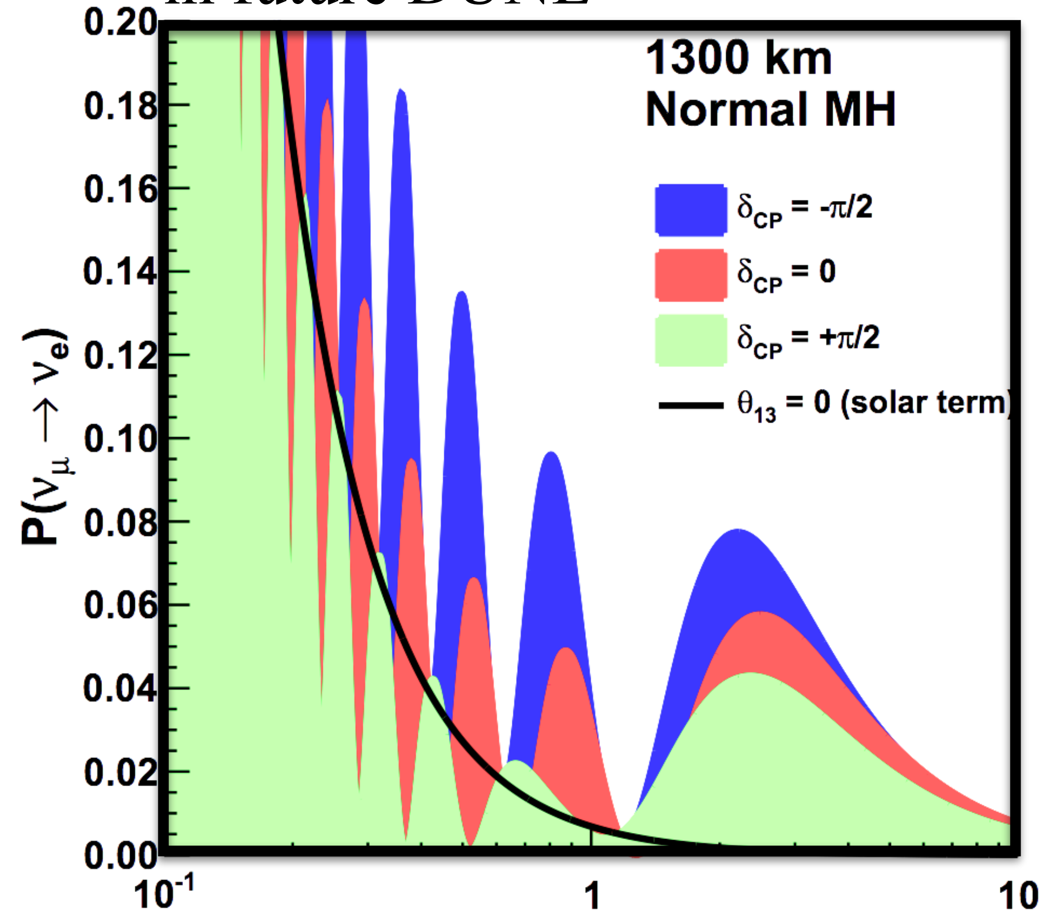


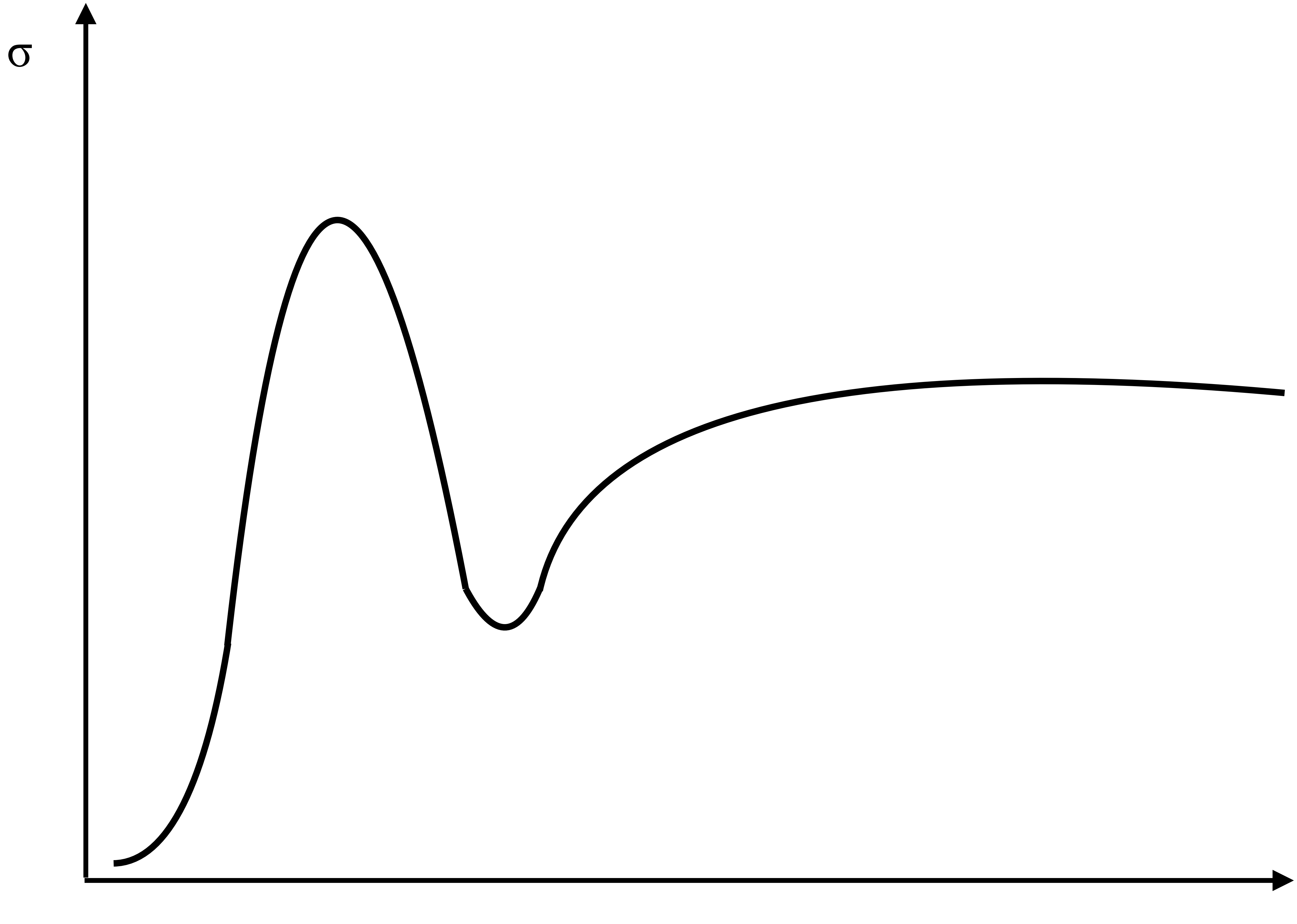
Neutrino Energy [GeV]

Simulation of oscillation effects in future DUNE

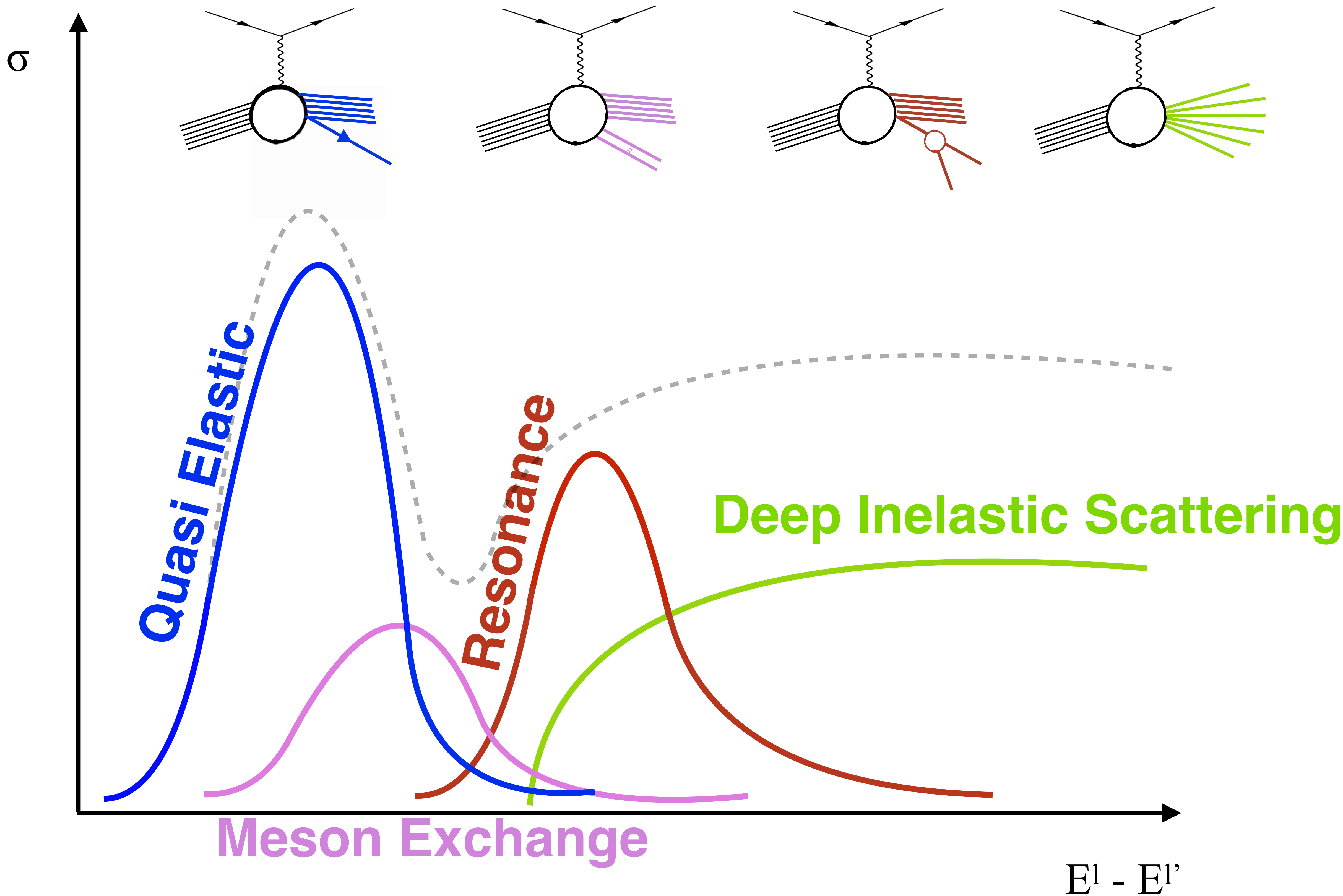


Neutrino Energy [GeV]

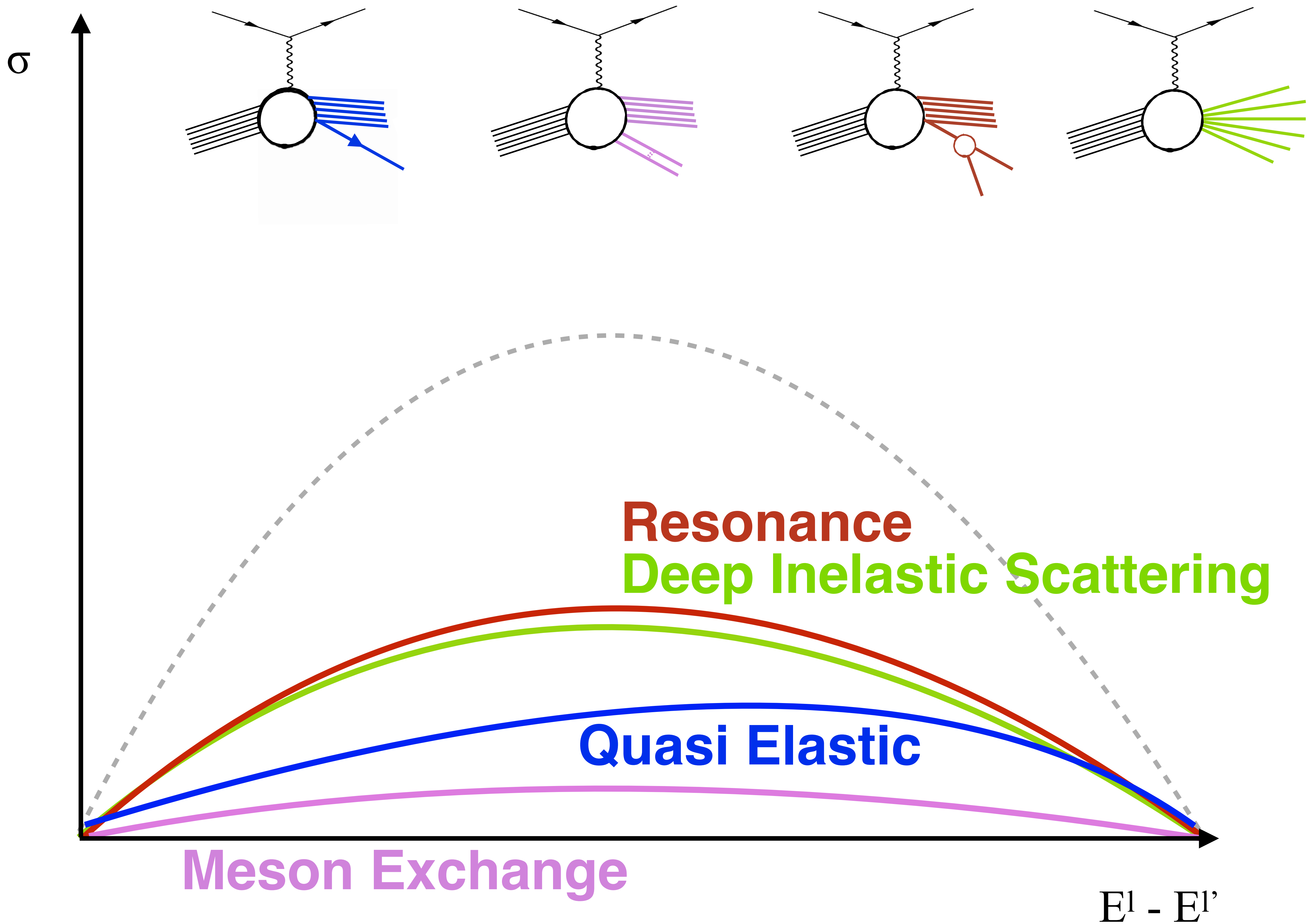
E Reconstruction Requires Interaction Modelling



E Reconstruction Requires Interaction Modelling



ν Reconstruction Requires Interaction Modelling



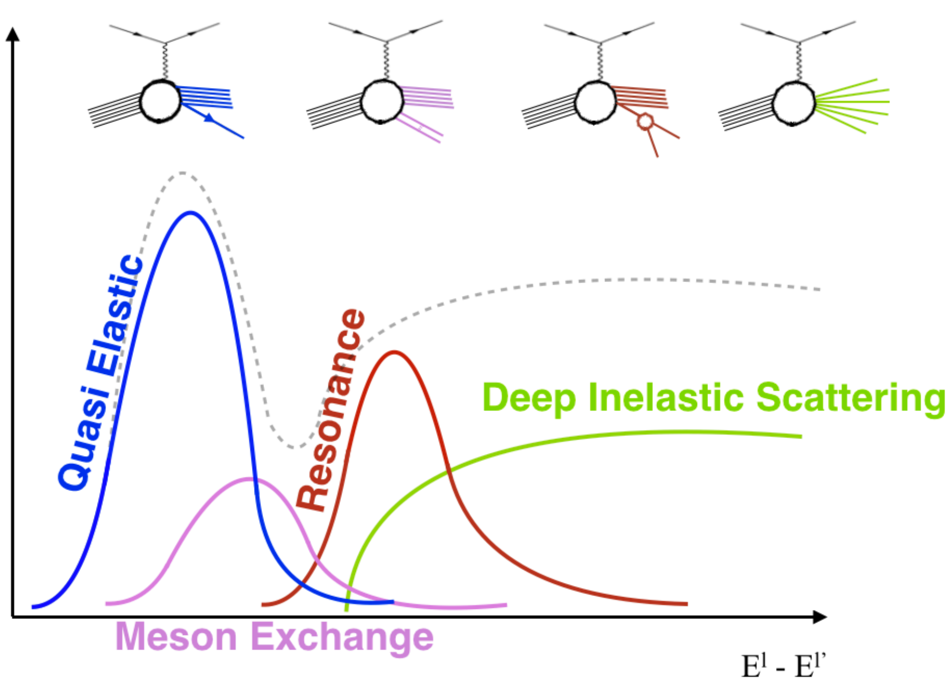
Lepton-Nucleus Interaction Modelling - Need constraints

Neutrino event generators simulating νA interaction

Genie

GiBUU
The Giessen Boltzmann-Uehling-Uhlenbeck Project

and more



Factorisation of

- Initial state
- Each interaction mechanism separately
- Final State Interactions

Empirical or semi classical models with many free parameters

The challenge - next generation high precision

$$N(E_{rec}, L) \propto \int \Phi(E, L)\sigma(E) f_\sigma(E, E_{rec}) dE$$

Measurement

Incoming true flux

Modelling input

- Improve theory
- Use near detector
- Use external constraints

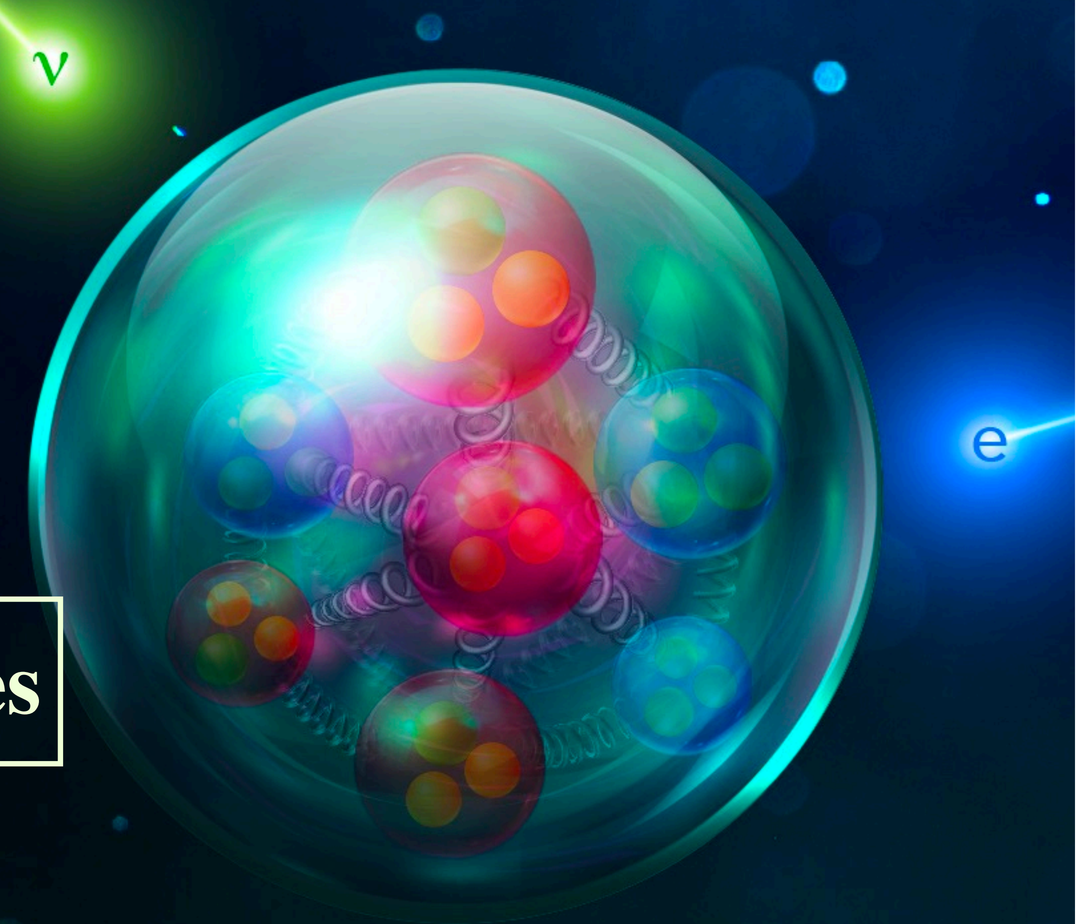
νA scattering

eA scattering

Why electrons?

Electrons and Neutrinos have:

- **Identical initial nuclear state**
- **Same Final State Interactions**
- **Similar interactions (vector vs. vector + axial)**



Useful to constrain model uncertainties

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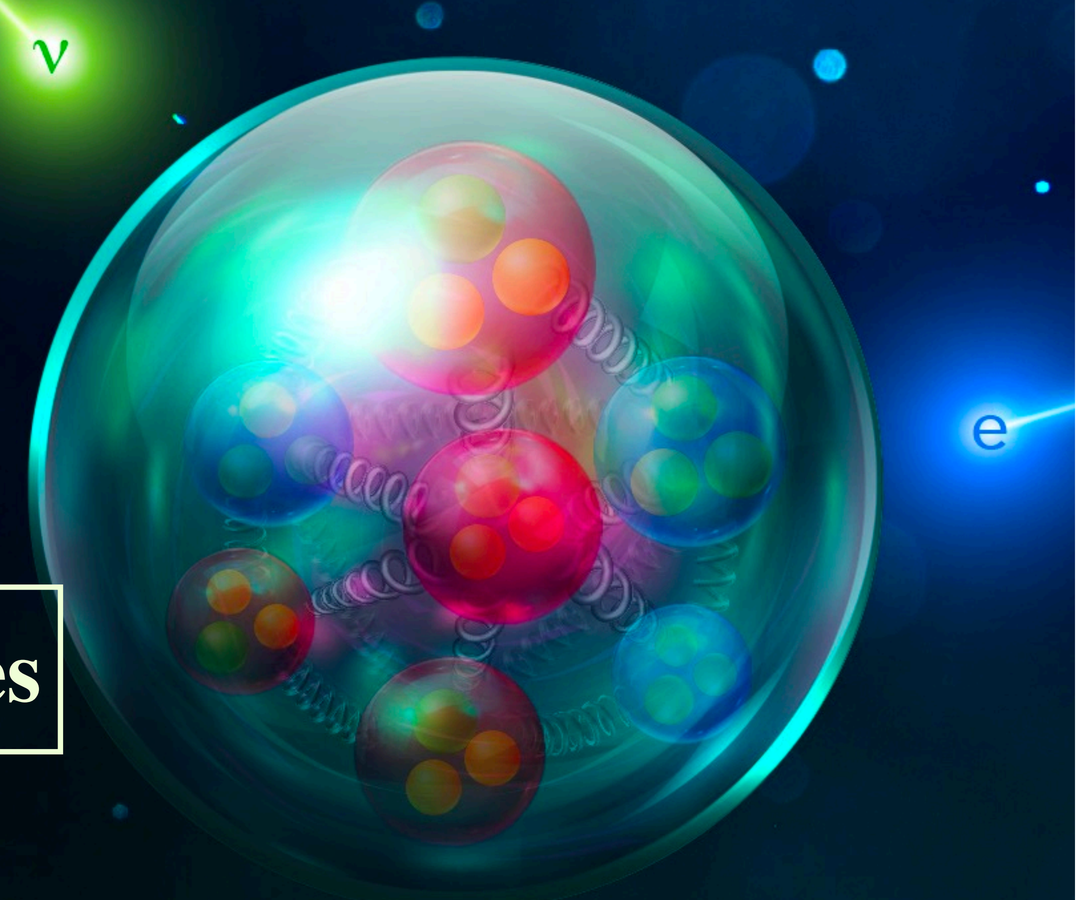
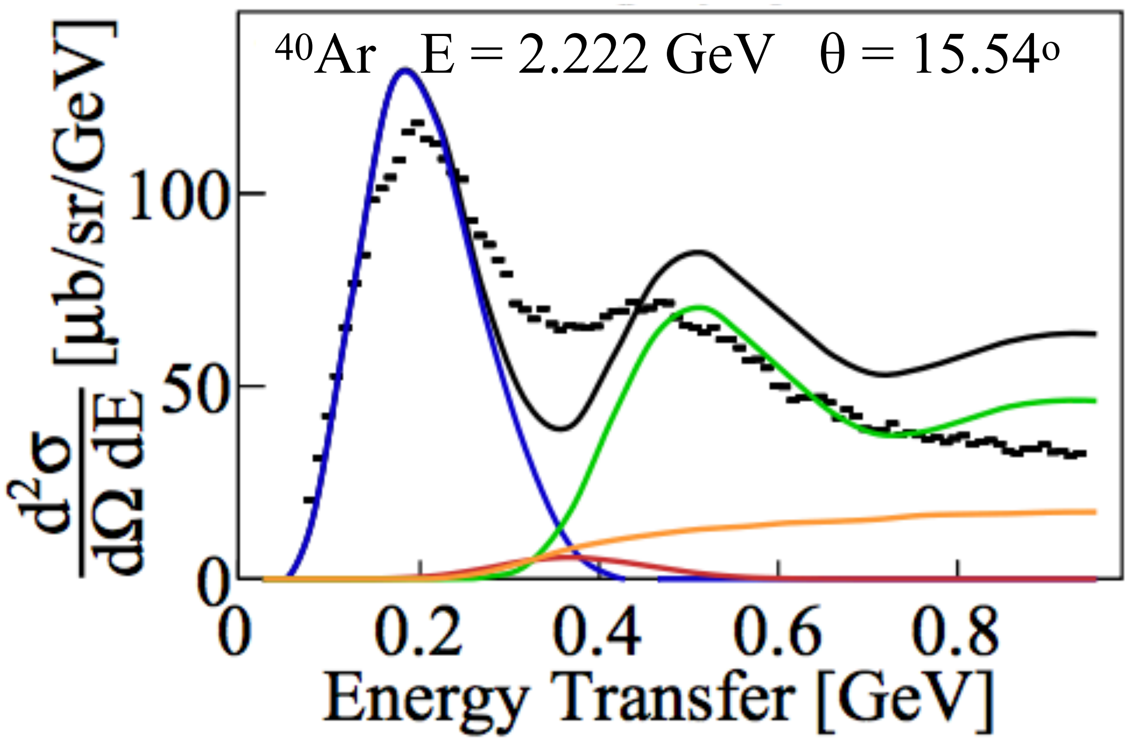
Useful to constrain model uncertainties

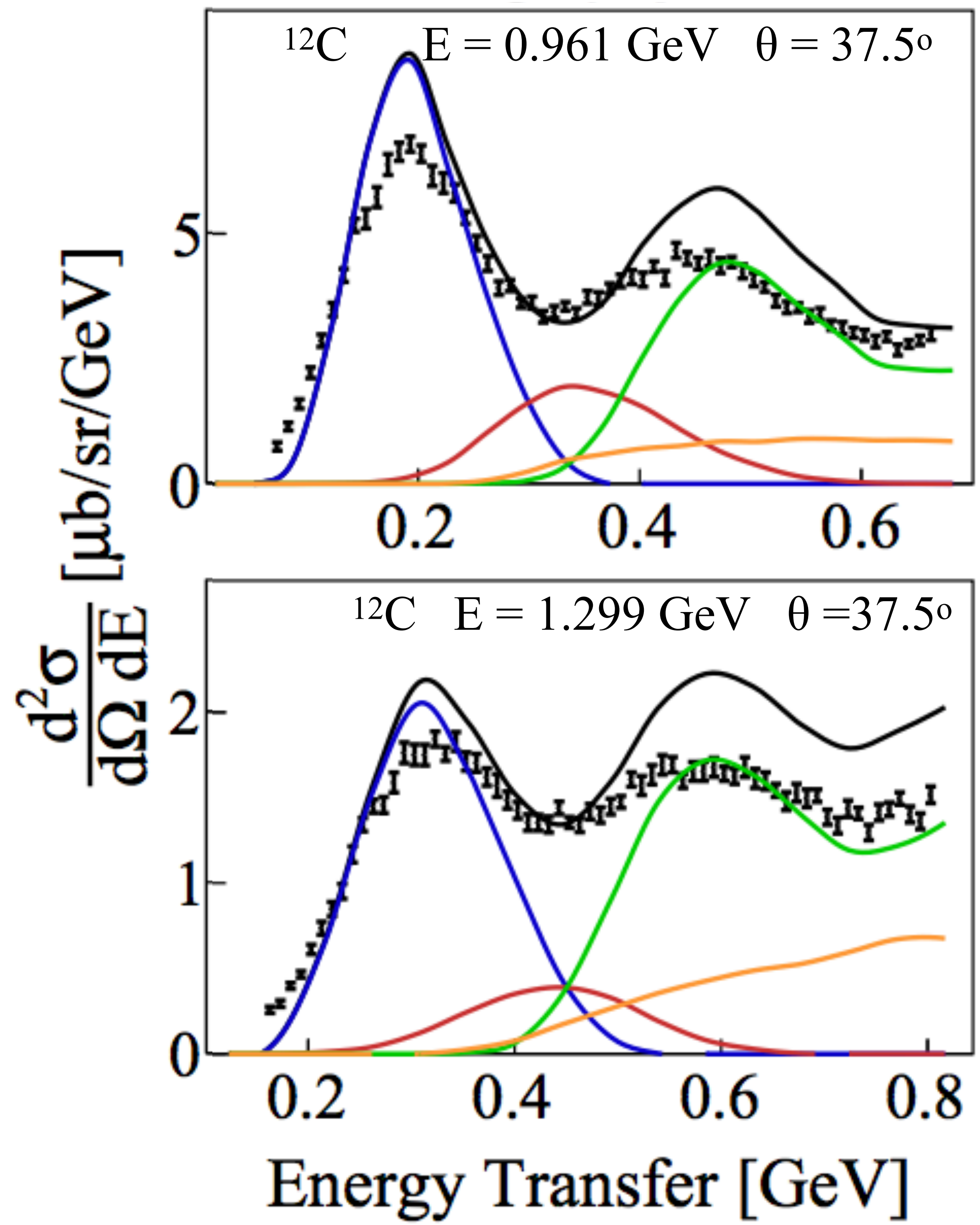


Electrons have known energies

Useful to test incoming energy reconstruction methods

Inclusive e data and generators





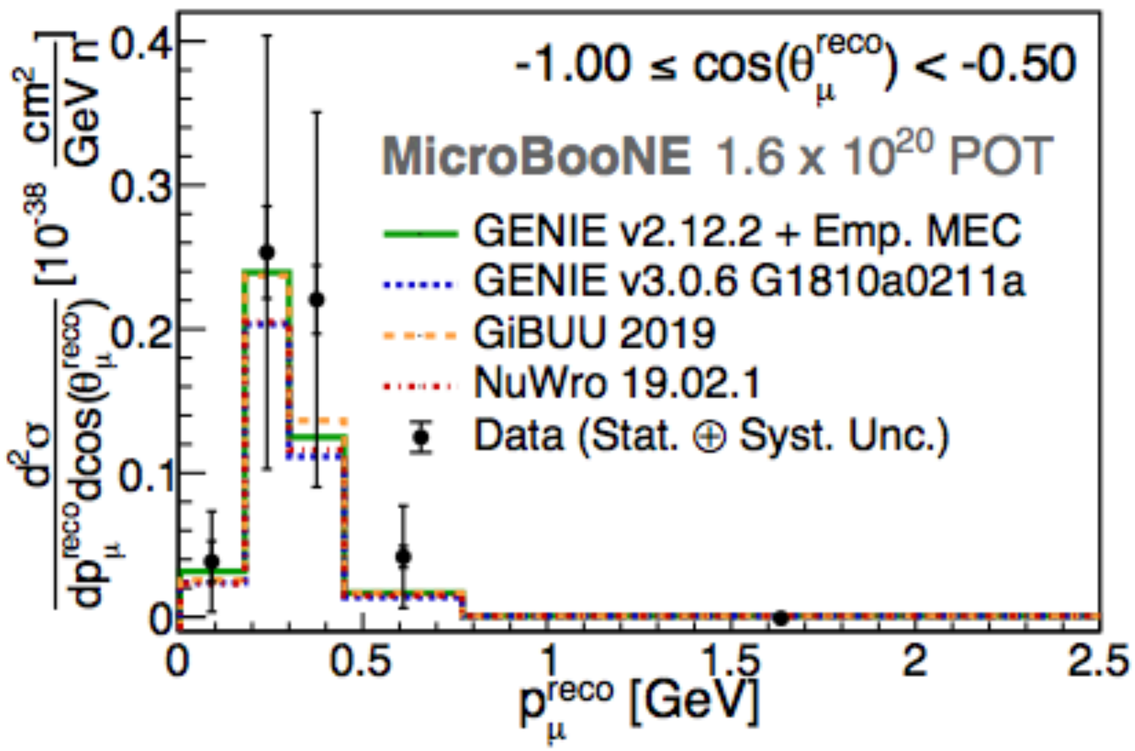
Genie

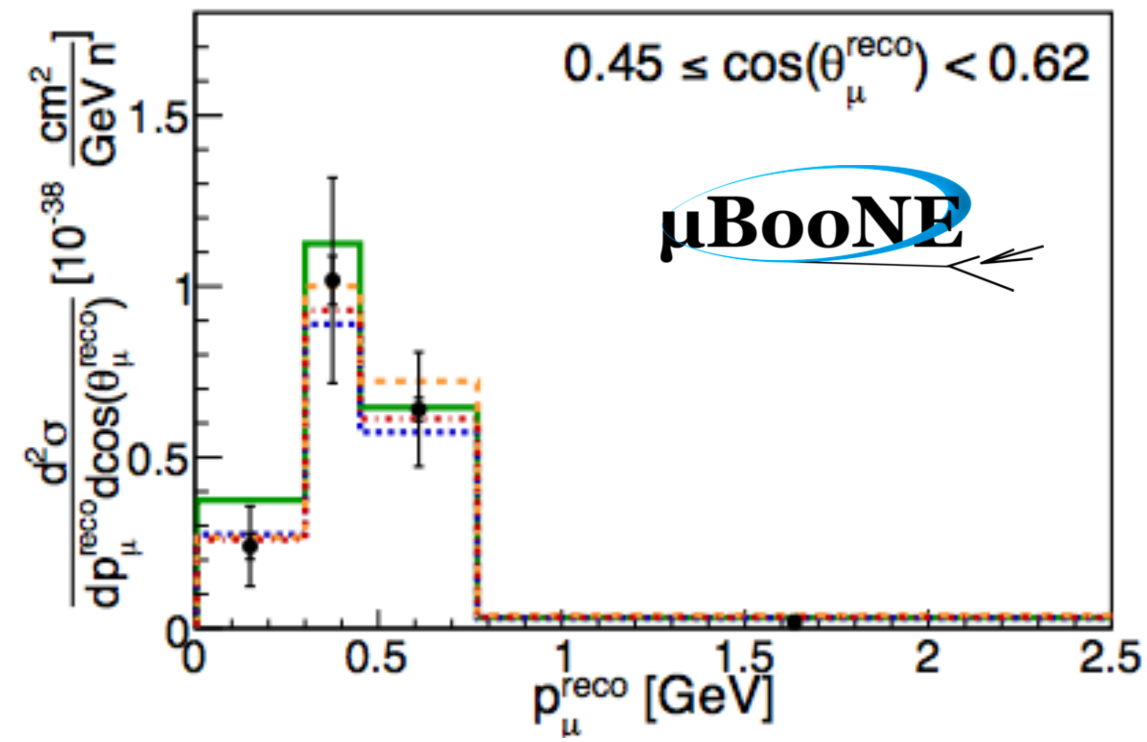
v3.0.6 tune G18_10a_02_11a

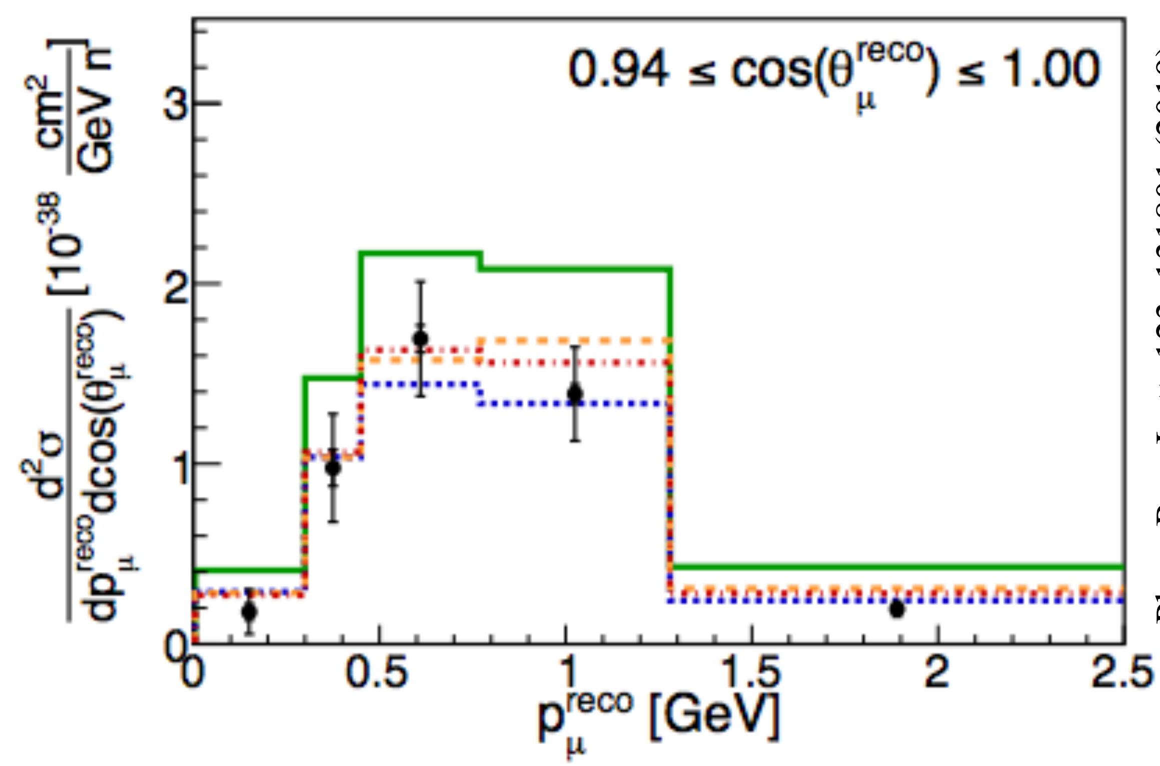
— Phys.Rev.D 103 (2021) 113003

Most eA inclusive measurements are in limited phase space for limited nuclei lacking exclusive hadron production measurements

Inclusive ν data and Generators







Phys. Rev. Lett. 123, 131801 (2019)

Genie

···· v3.0.6 tune G18_10a_02_11a

Most νA inclusive still lacking statistics, using low energy beam

CLAS Detector

Electron beam with energies up to 6 GeV

Large acceptance

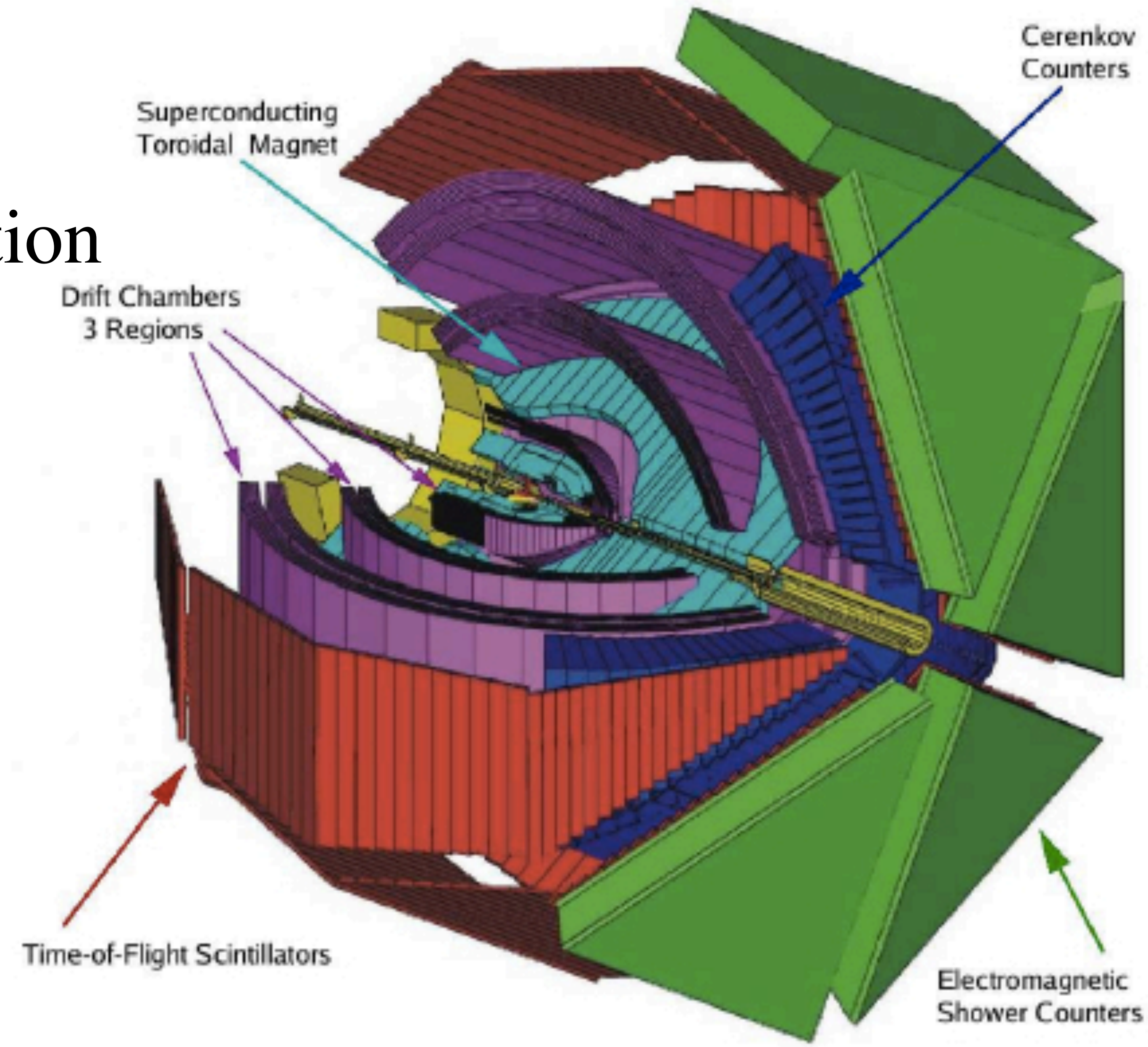
Charged particles above detection

threshold:

300 MeV/c for p

150 MeV/c for $P_{\pi}^{+/-}$

500 MeV/c for P_{π}^{0}



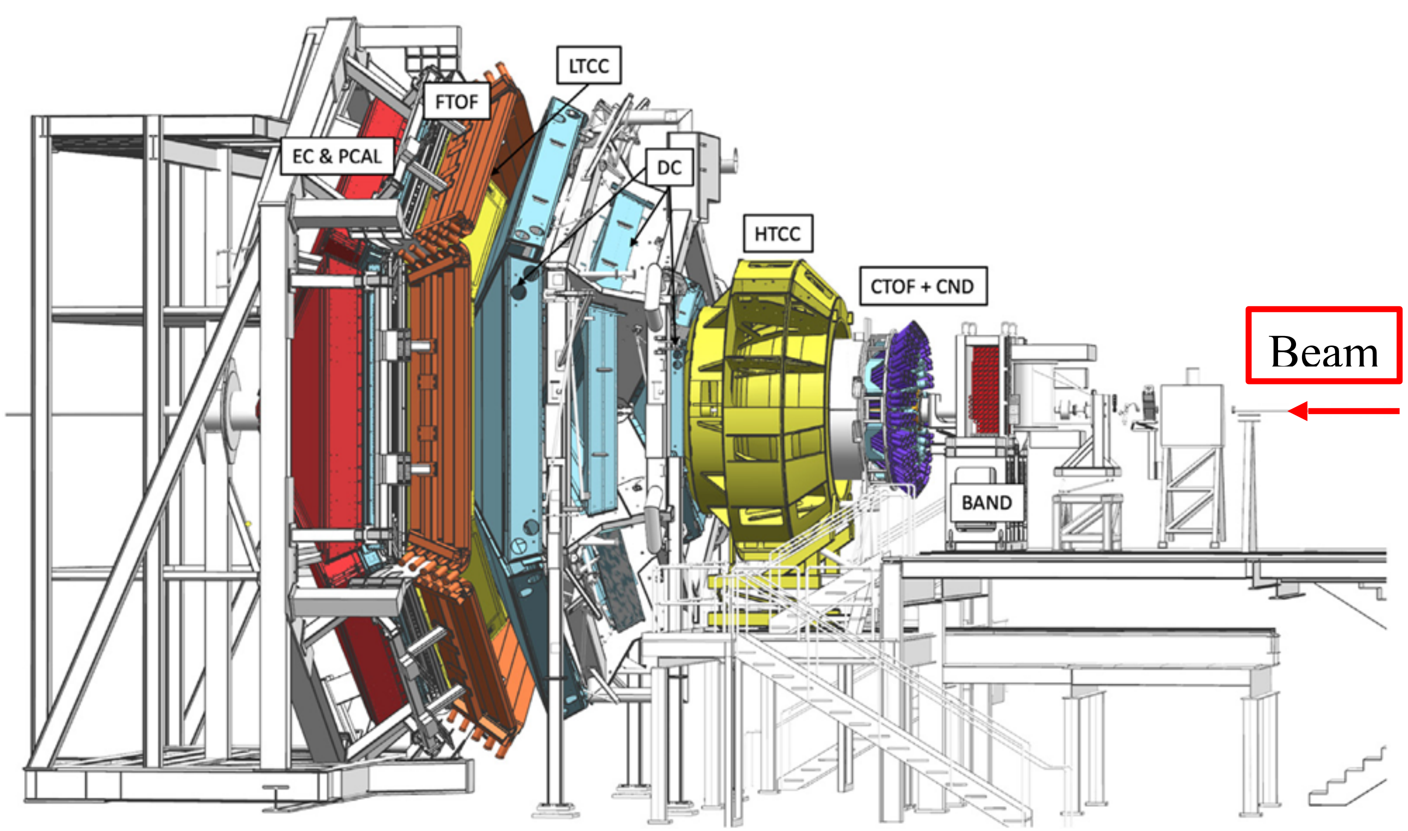
Open Trigger: 1,2,4 GeV, ^{12}C, ^{56}Fe

CLAS Detector

Electron beam with energies up to 6 GeV

Improved acceptance ($\theta_e > 5^o$)

High Luminosity 10^{35} $cm^{-2}s^{-1}$



Detection thresholds:

400 MeV/c for *p* and *n* (!)

200 MeV/c for $\pi^{\pm}$

300 MeV/c for γ

Open Trigger:

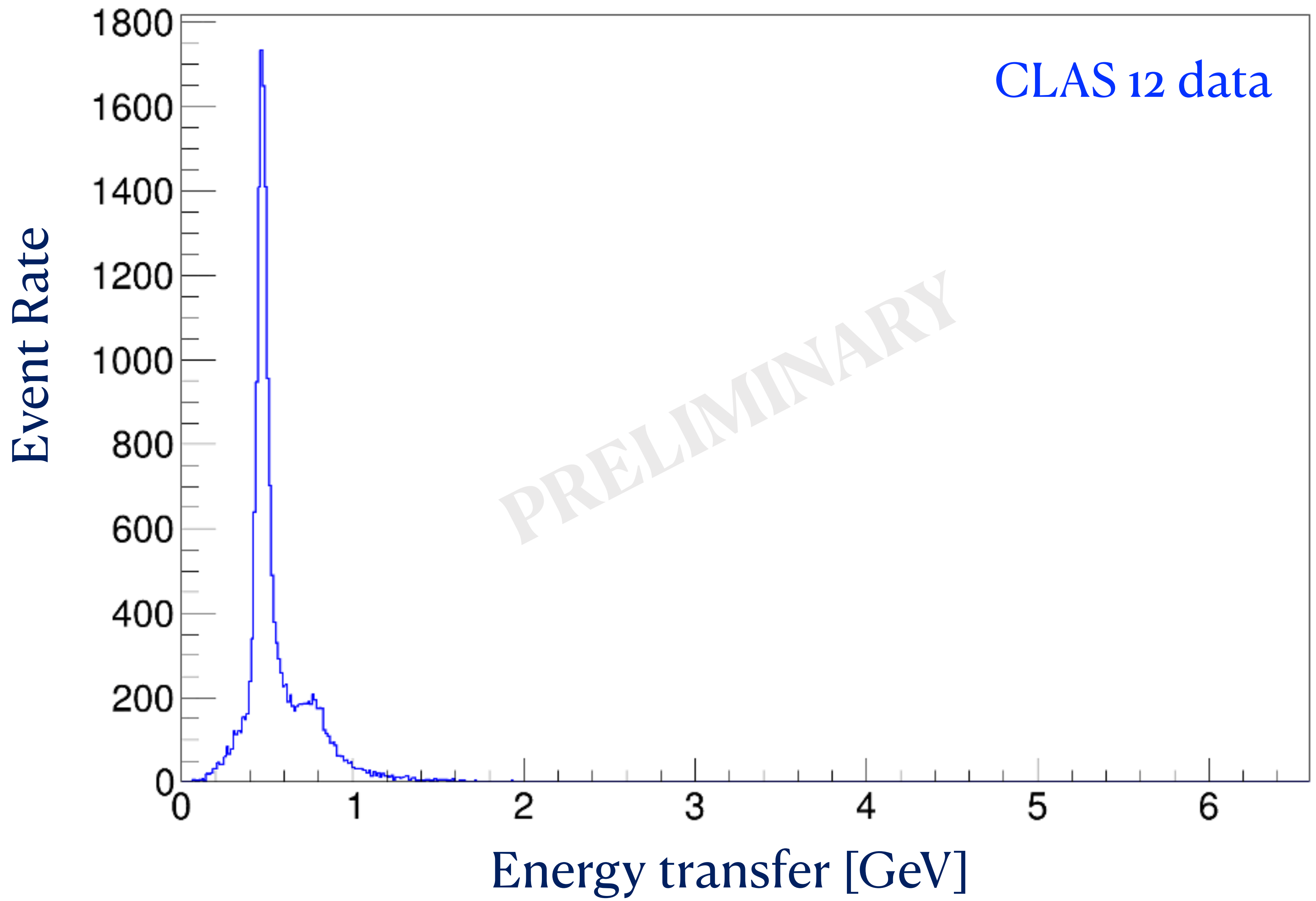
2,4,6 GeV

H, D, ^{4}He, ^{12}C, ^{40}Ar …

Towards new Inclusive results on Ar

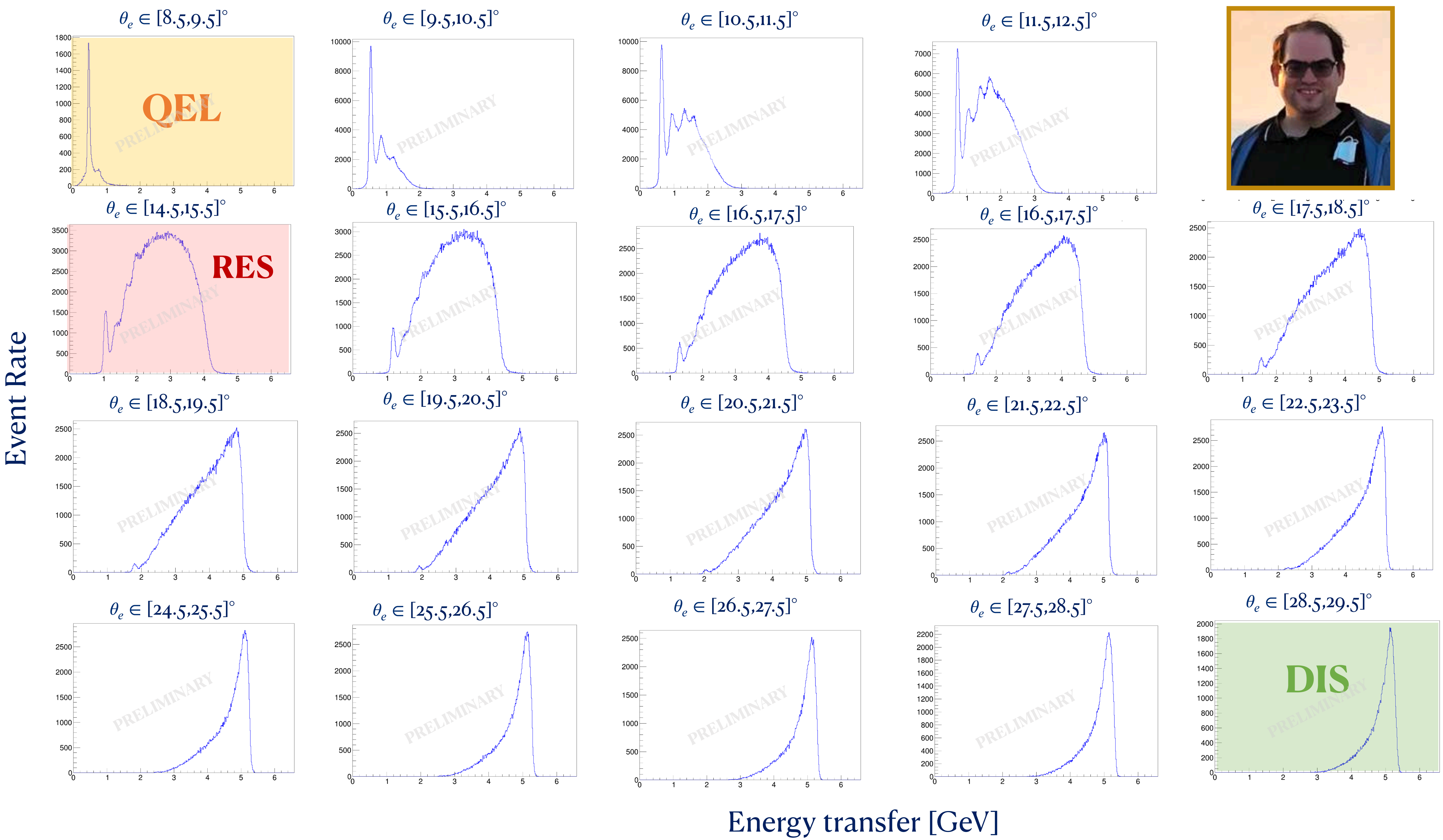
^{2}H at 6GeV

$\theta_e \in [10.5, 39.5]^\circ$ with 1° steps



Matan Goldenberg

Towards new Inclusive results on Ar



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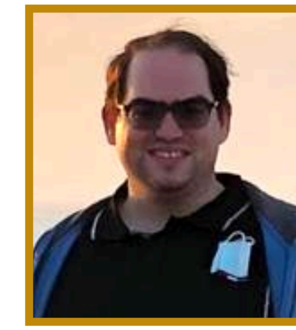
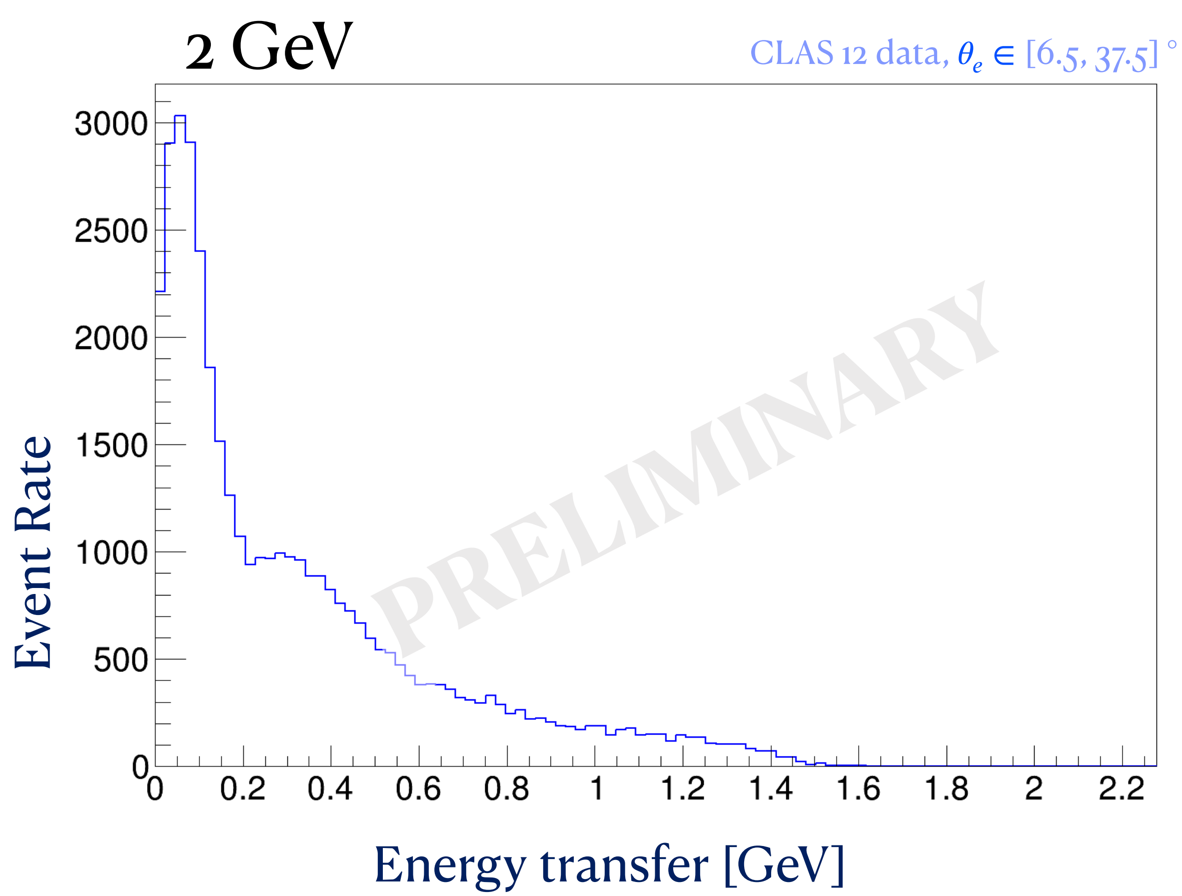
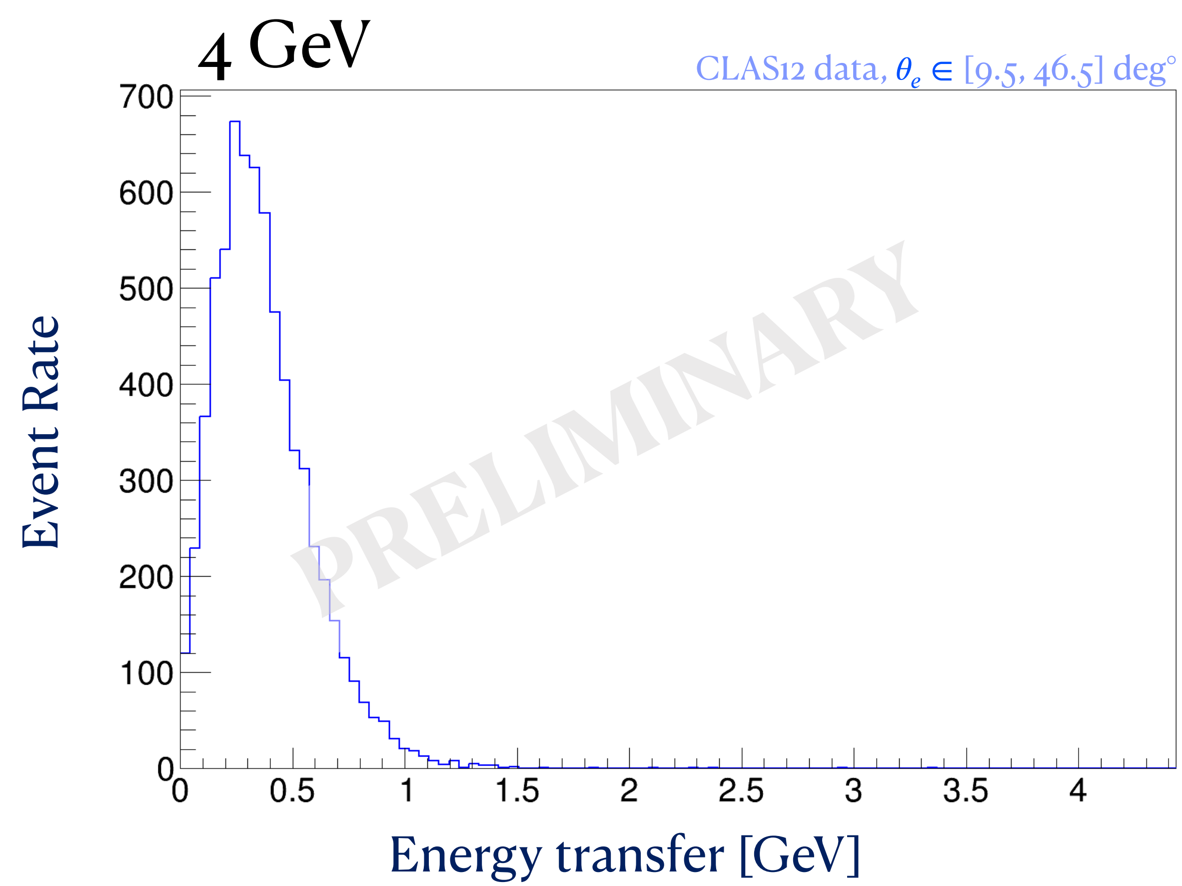


^{40}Ar





1p0π Event Selection

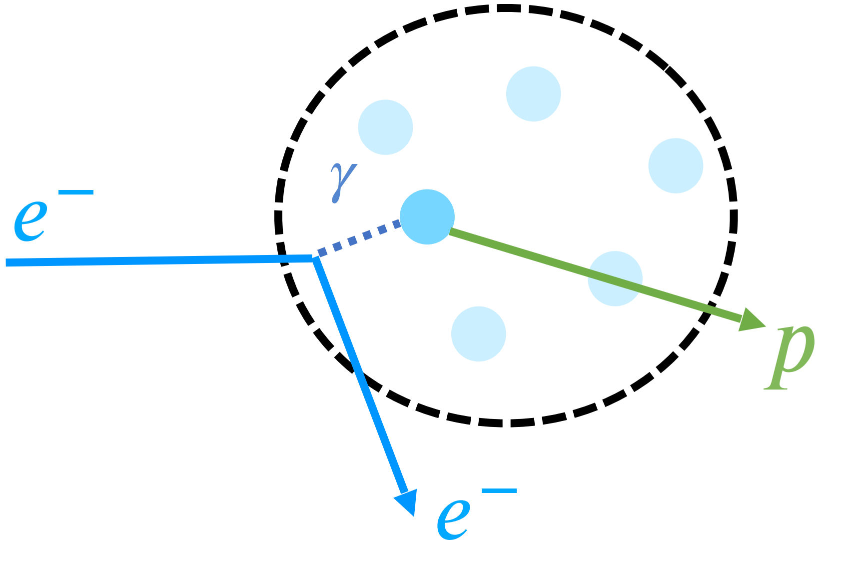
Focus on Quasi Elastic events:

1 proton above 300 MeV/c

no additional hadrons above detection threshold:

150 MeV/c for $P_{\pi^{+/-}}$

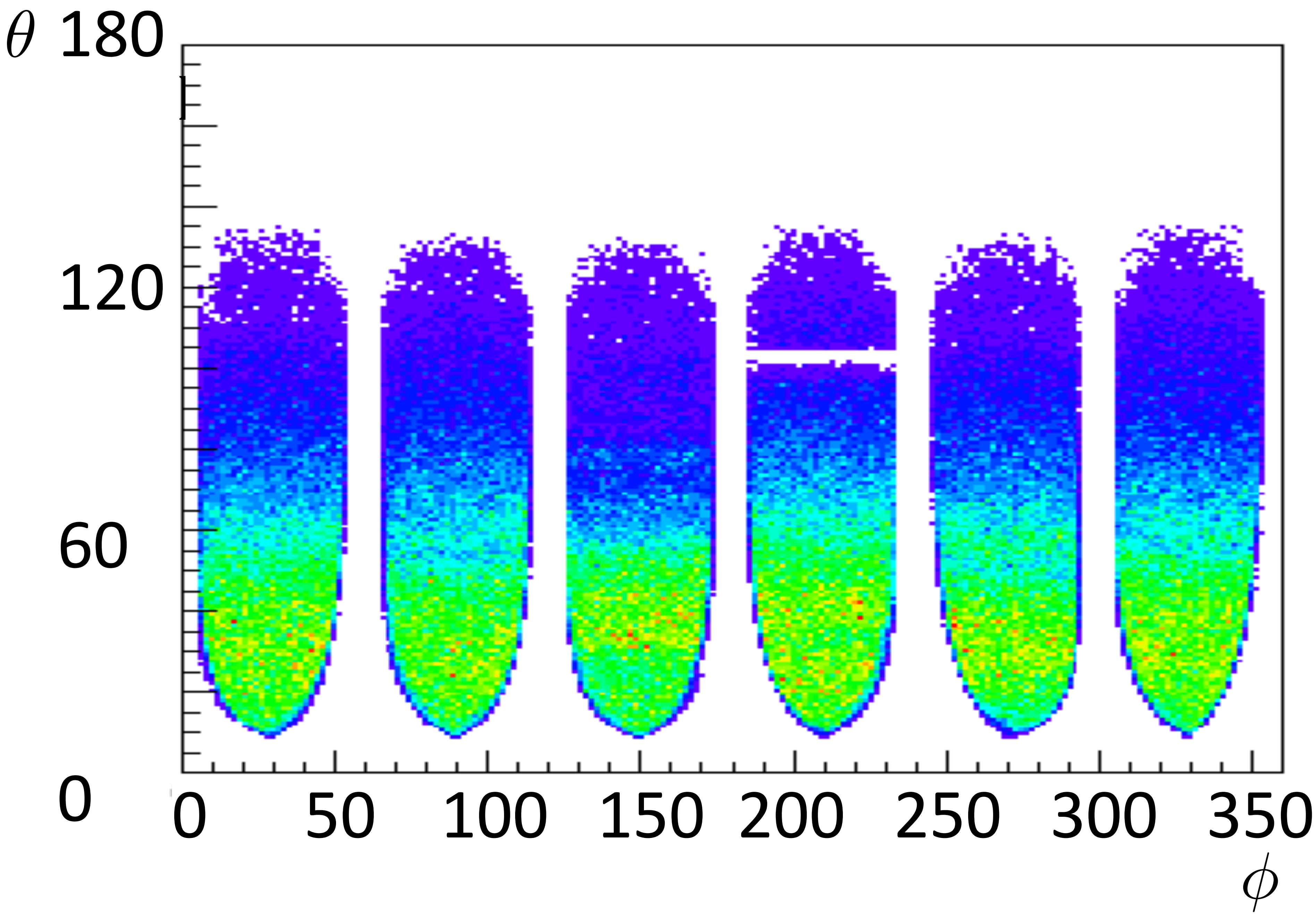
500 MeV/c for P_{π^0}

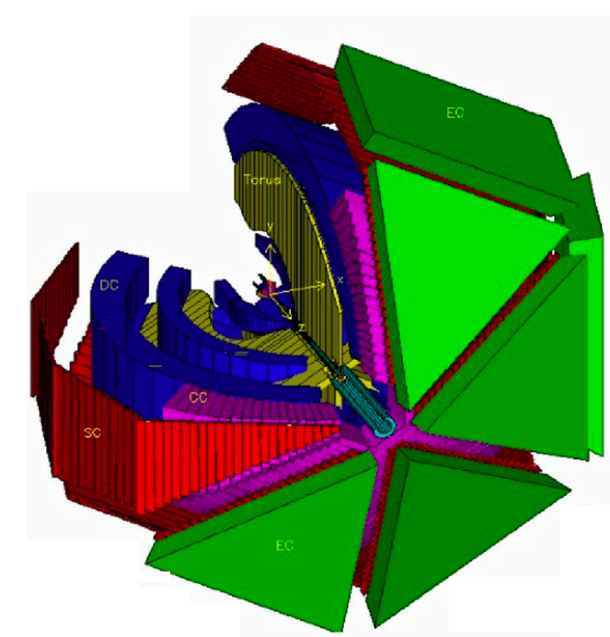


Background Subtraction

Different interaction lead to multi-hadron final states

Gaps can make them loop like QE-like events with outgoing 1μ1p





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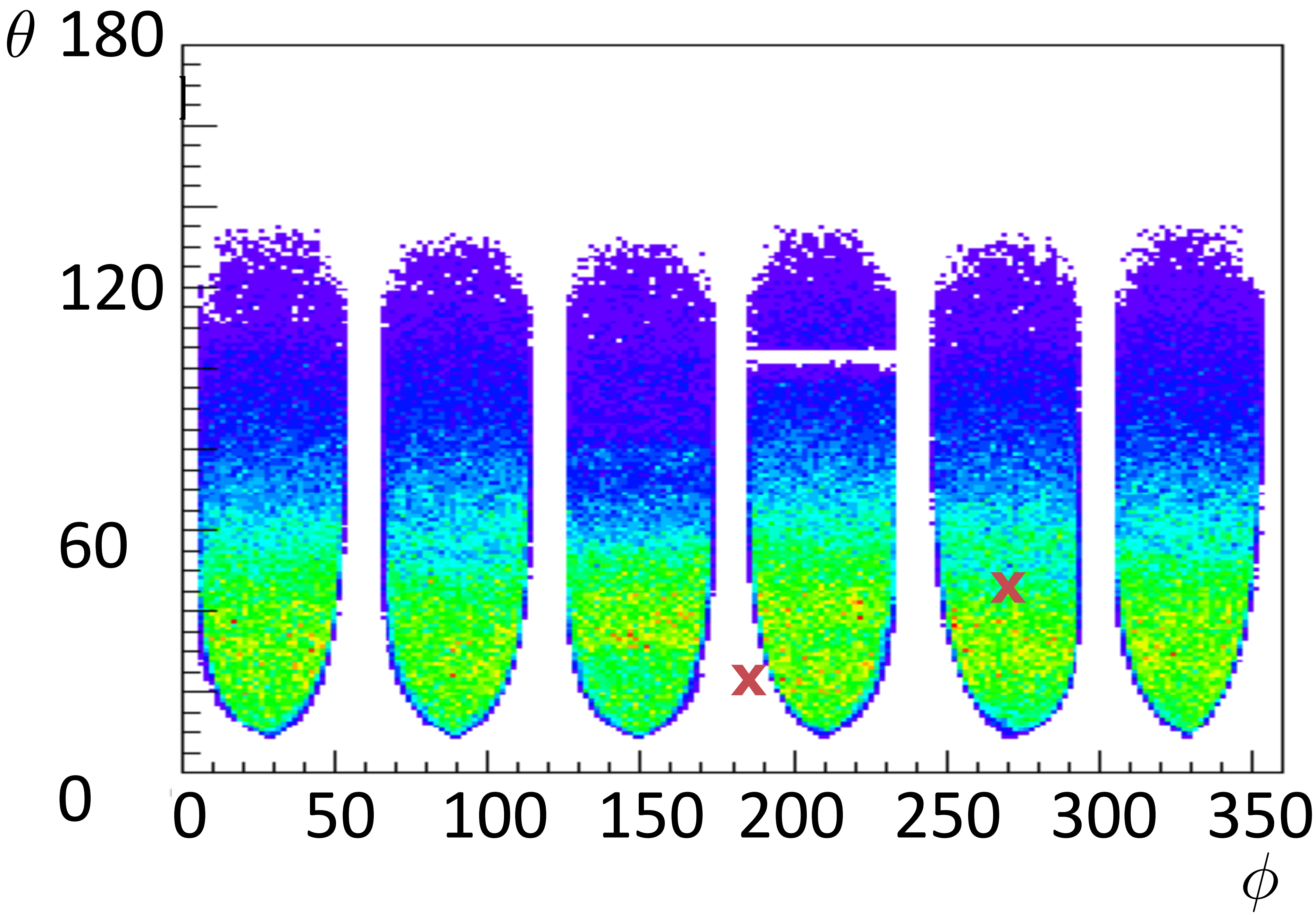
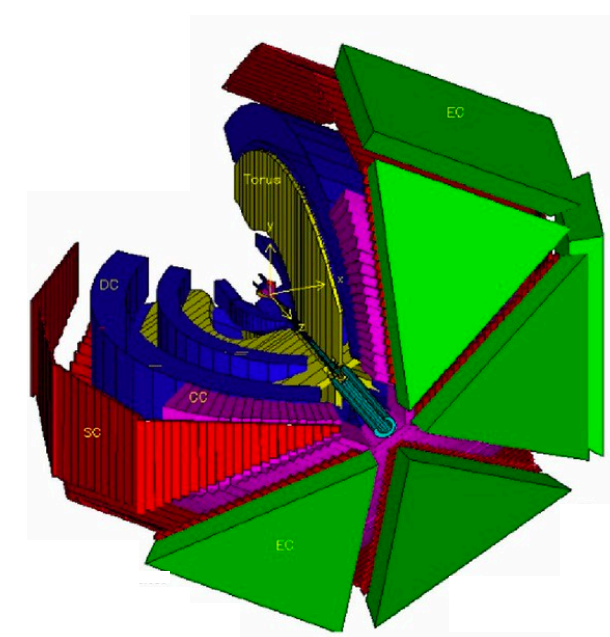
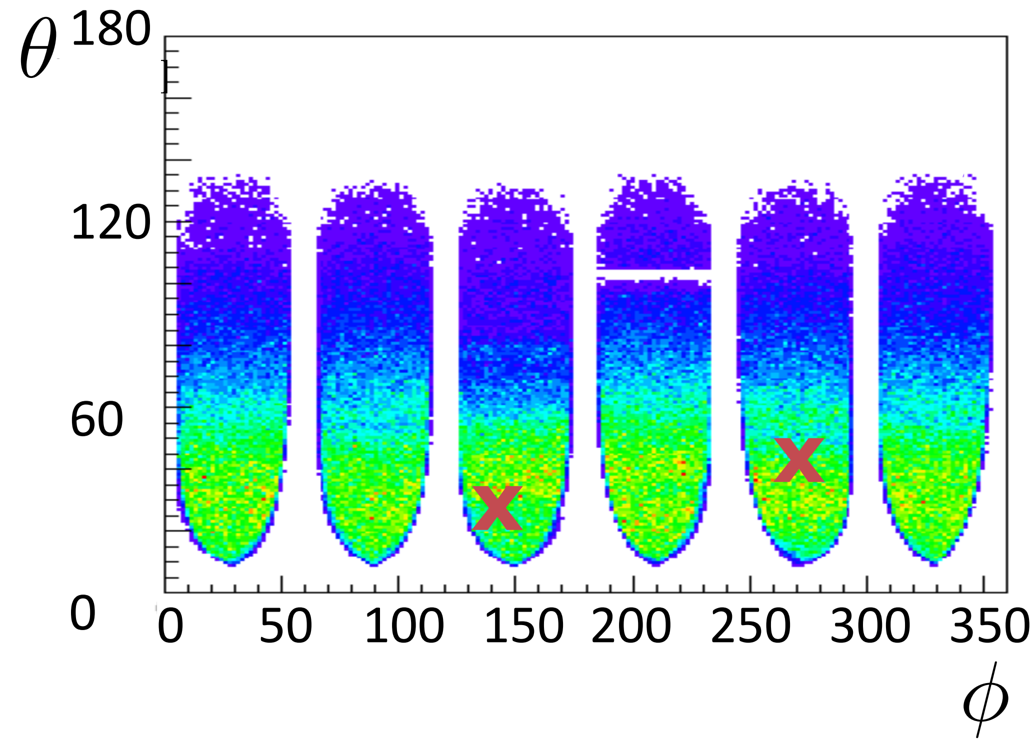
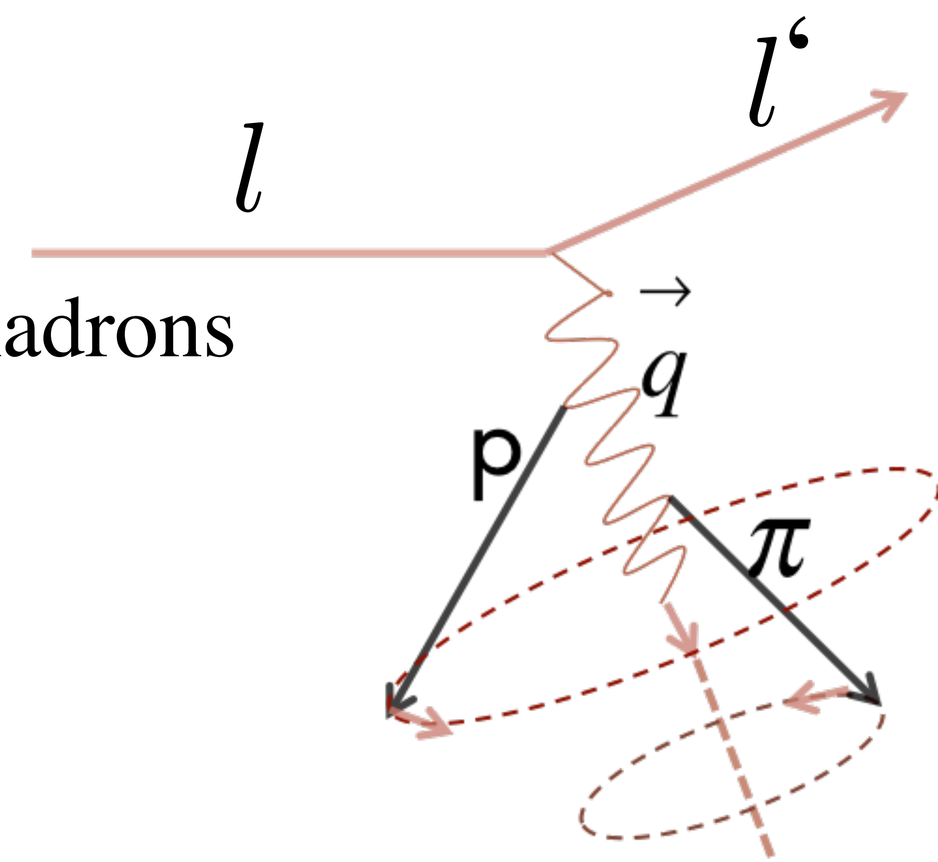




Data Driven Background Subtraction

- Using measured (e,e'pπ) events
- Rotate p,π around **q**
- Determine event acceptance
- Subtract (e,e'pπ) contribution



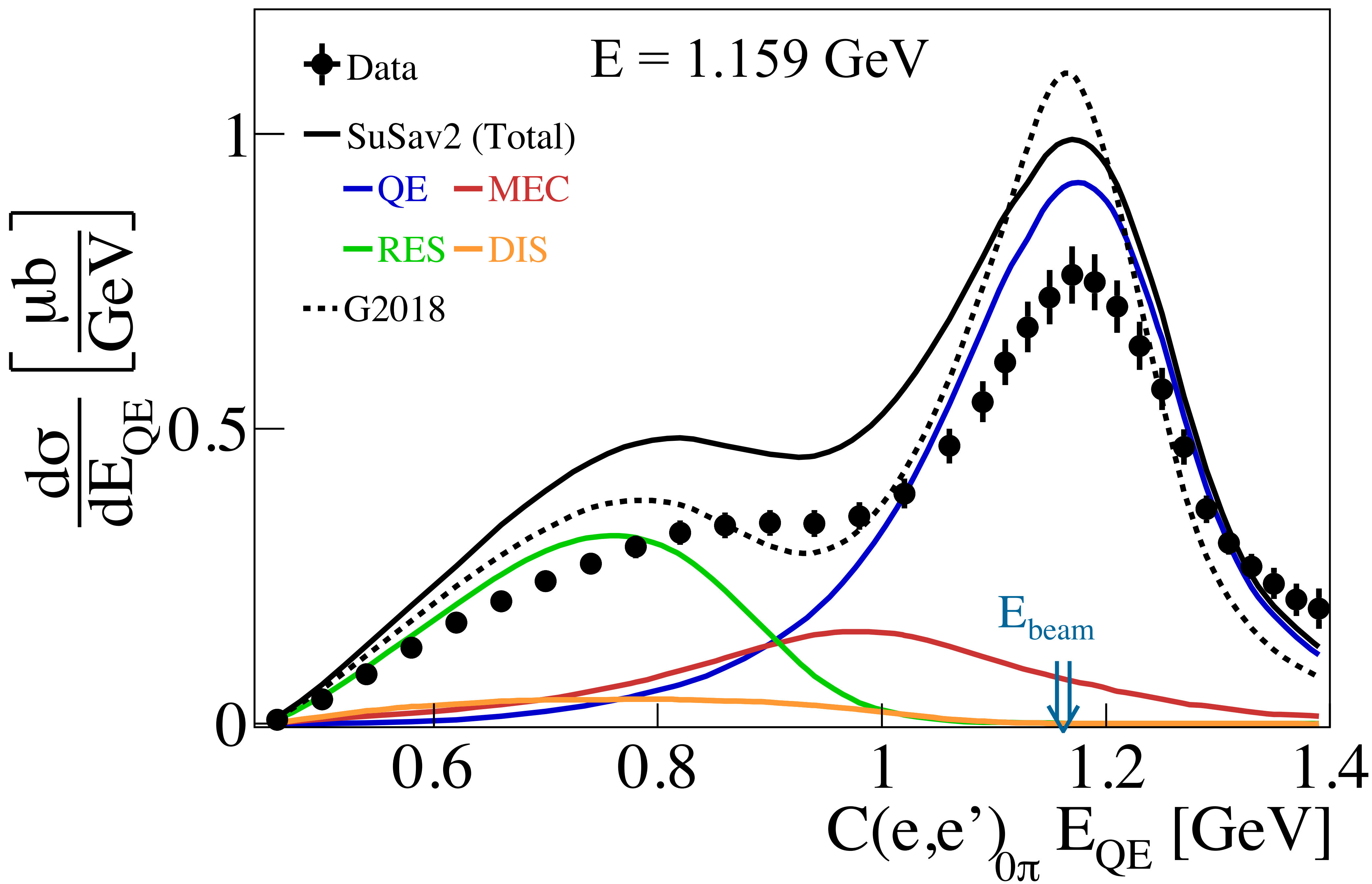


- Same for final states with more than 2 hadrons

Julia
Tena Vidal

Data

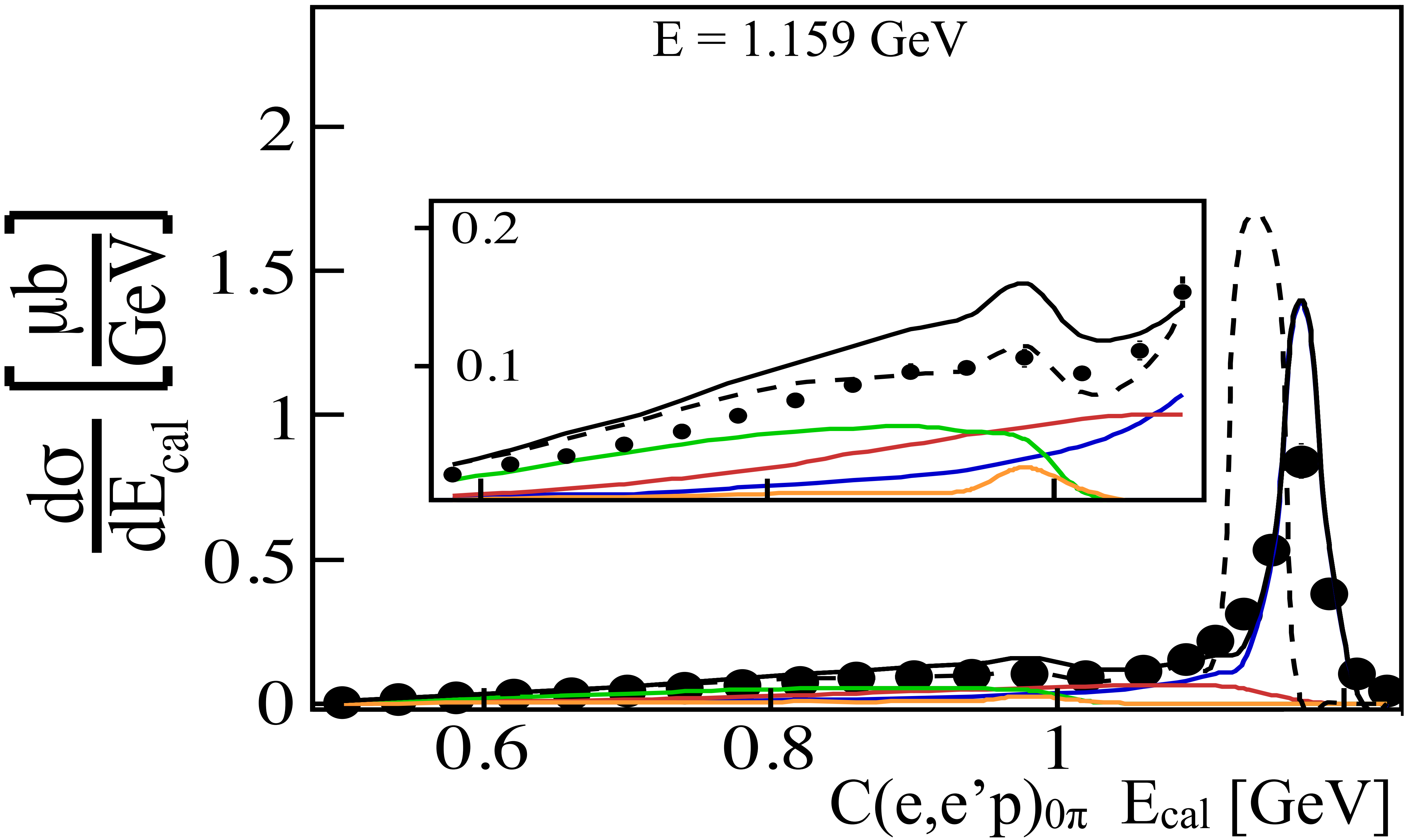
Inclusive Energy Reconstruction



Nature **599**, 565 (2021)

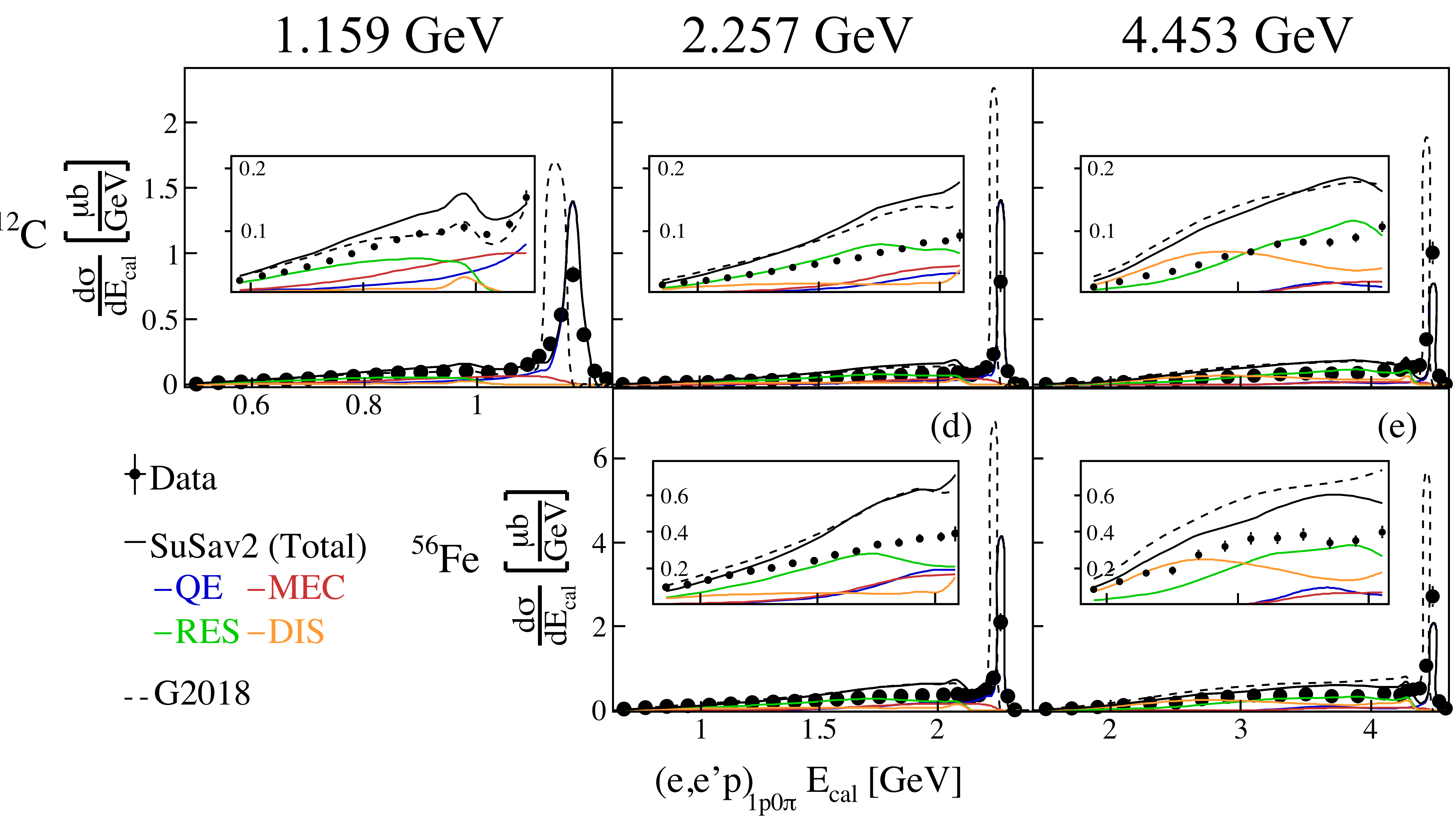
$$E_{QE} = \frac{2M\epsilon + 2ME_l - m_l^2}{2(M - E_l + |k_l| \cos\theta_l)}$$

Reconstructed Calorimetric Energy



Nature **599**, 565 (2021)

Reconstructed Calorimetric Energy



Nature **599**, 565 (2021)

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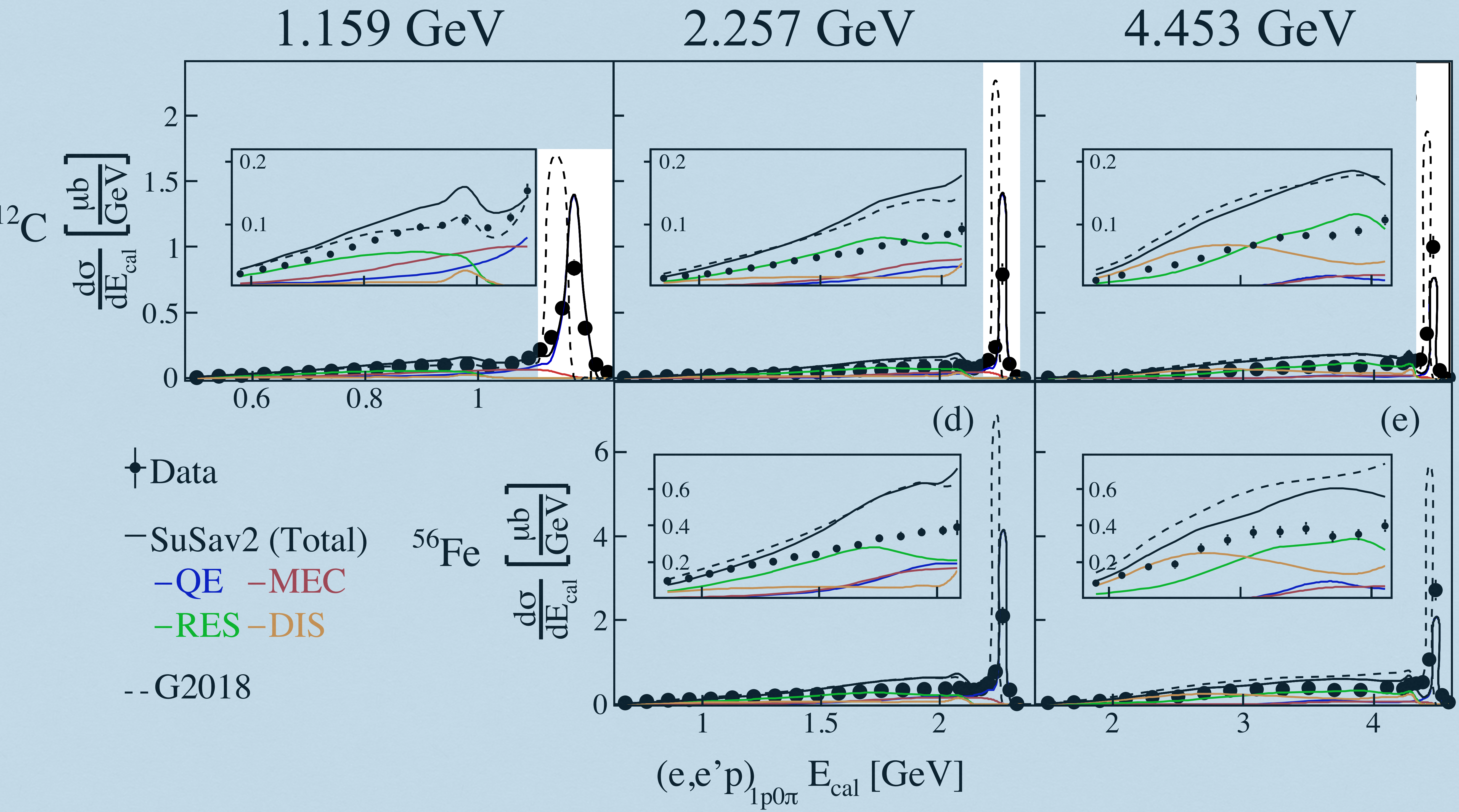

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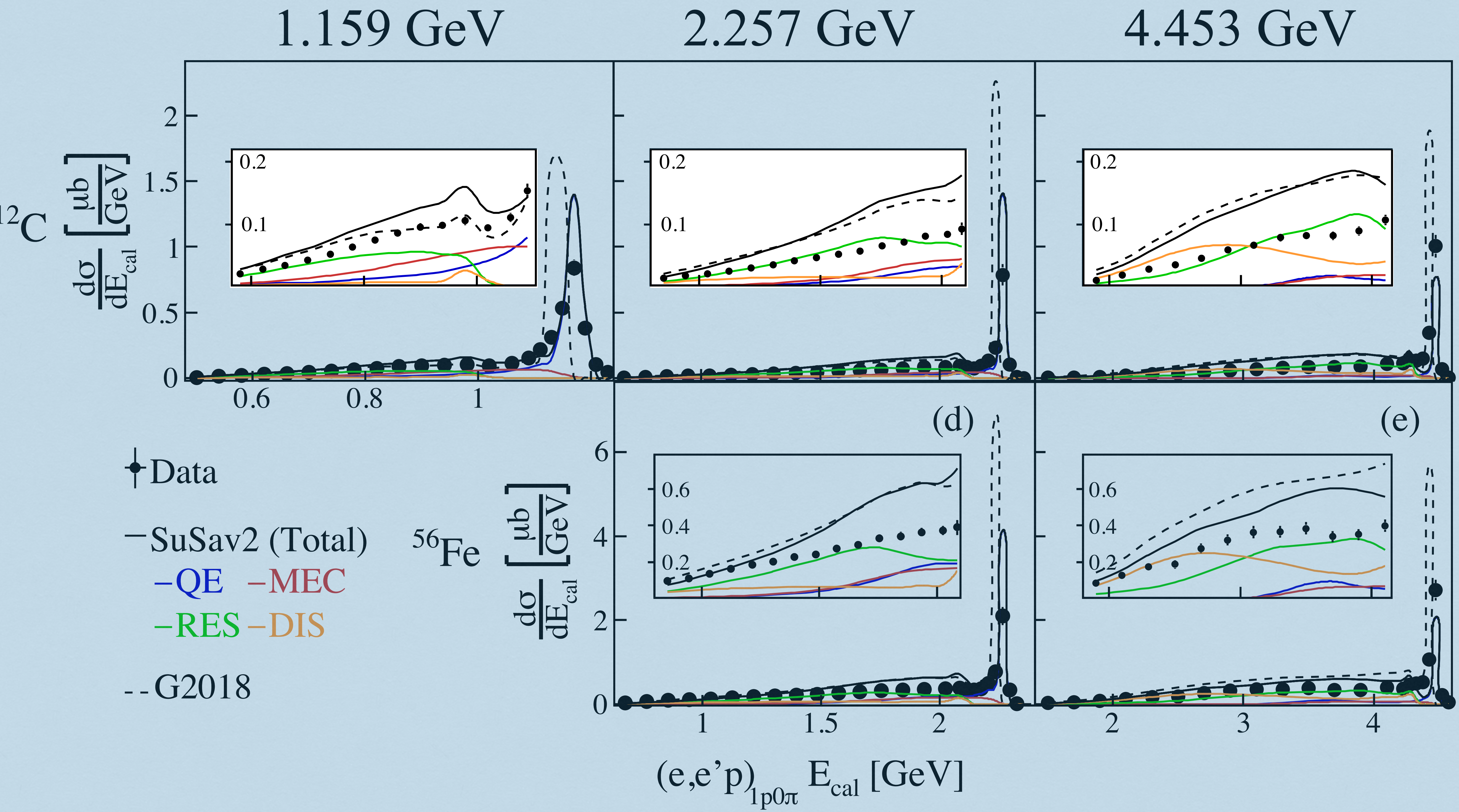
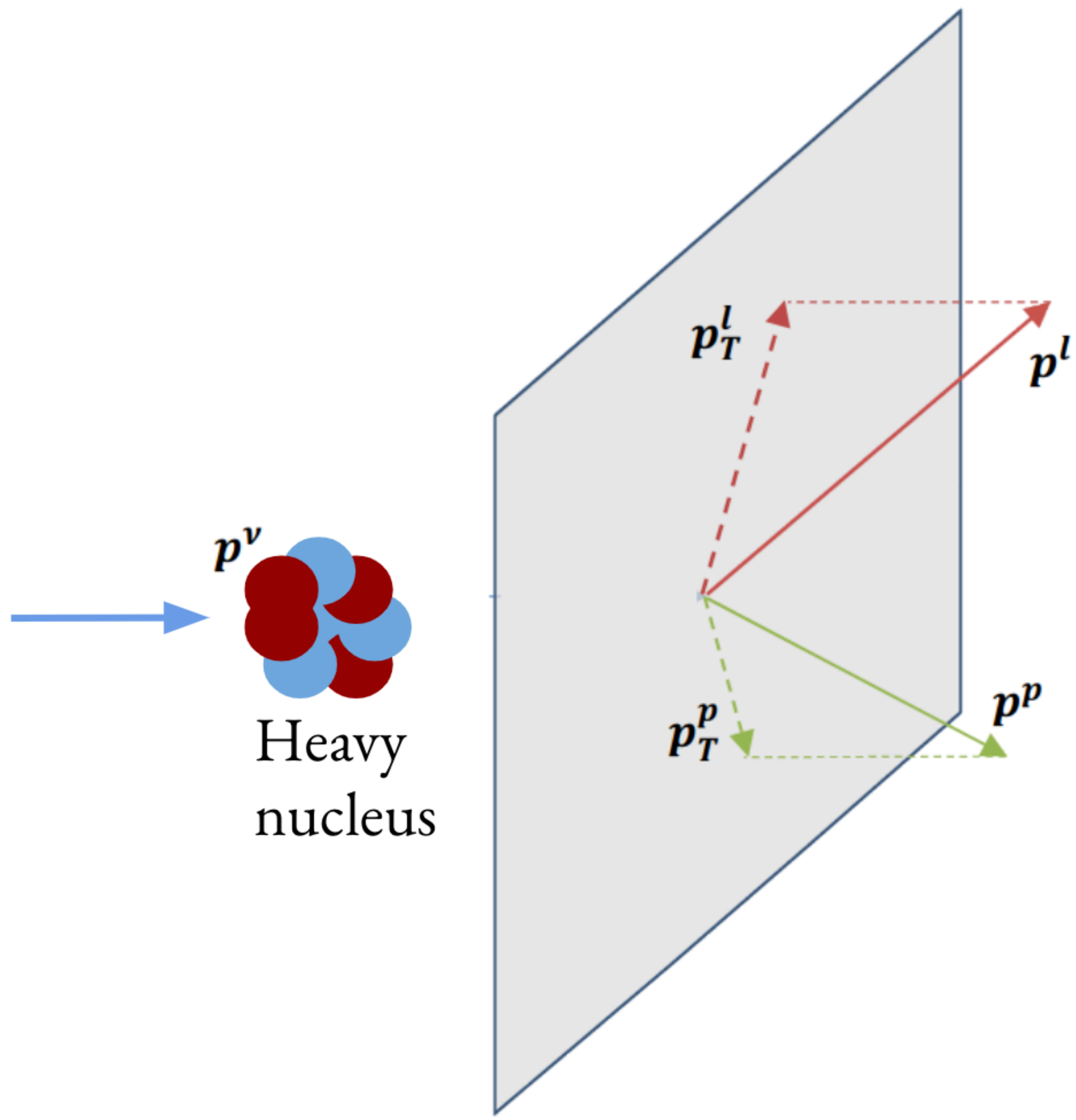
Reconstructed Calorimetric Energy

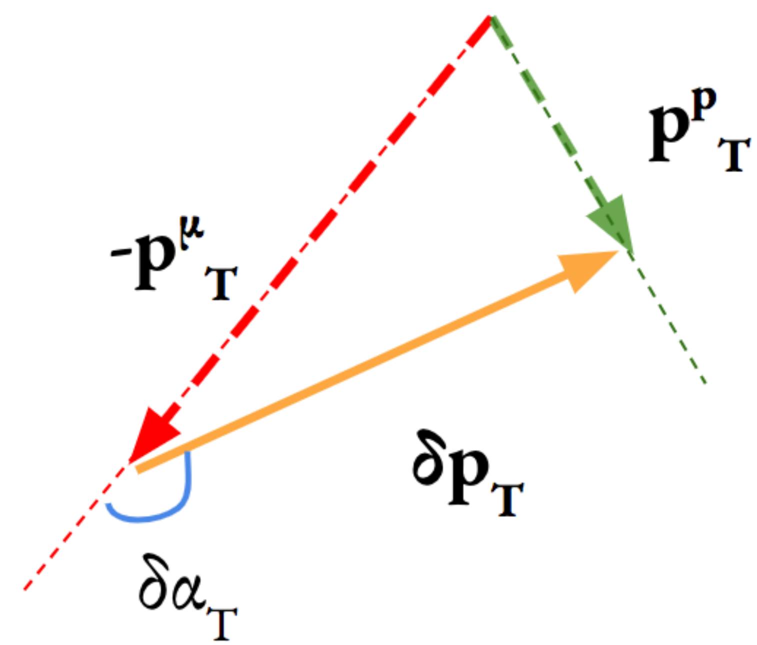


Nature **599**, 565 (2021)

Focusing on different reaction mechanisms

Standard Transverse Variables





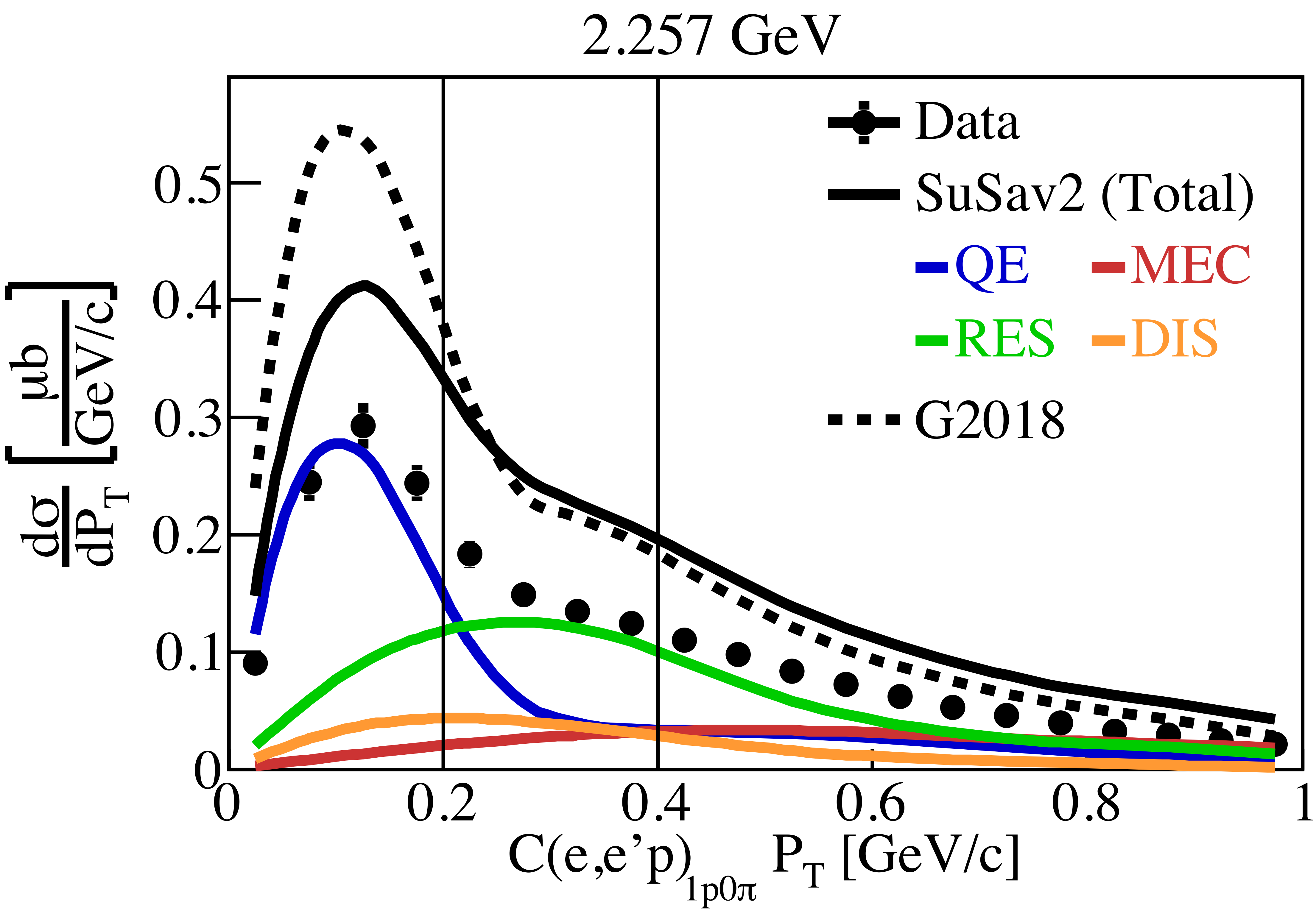
$$\vec{P}_T = \vec{P}_T^{e'} + \vec{P}_T^{p}$$

Sensitive to
hit nucleon momentum

$\delta\alpha_T$

Sensitive to
Final State Interactions

Transverse missing momentum



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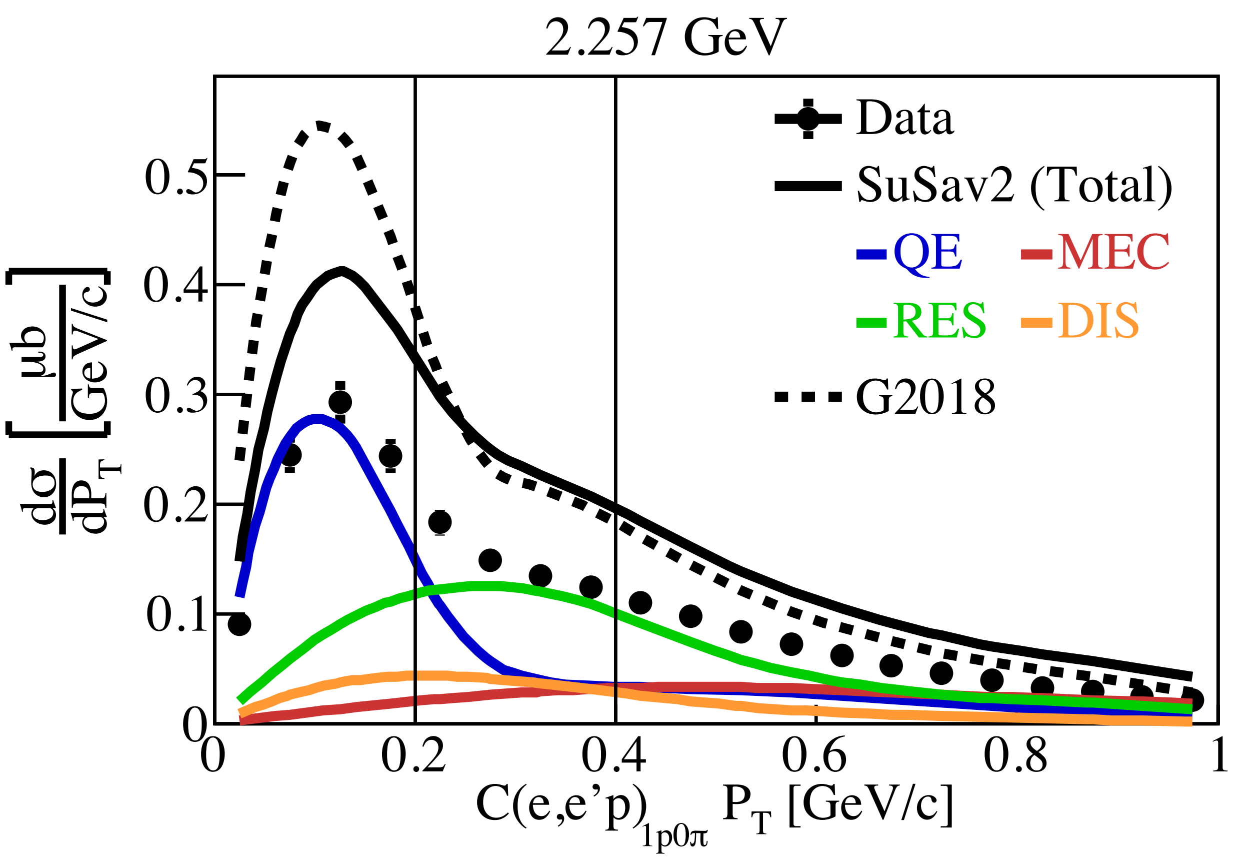
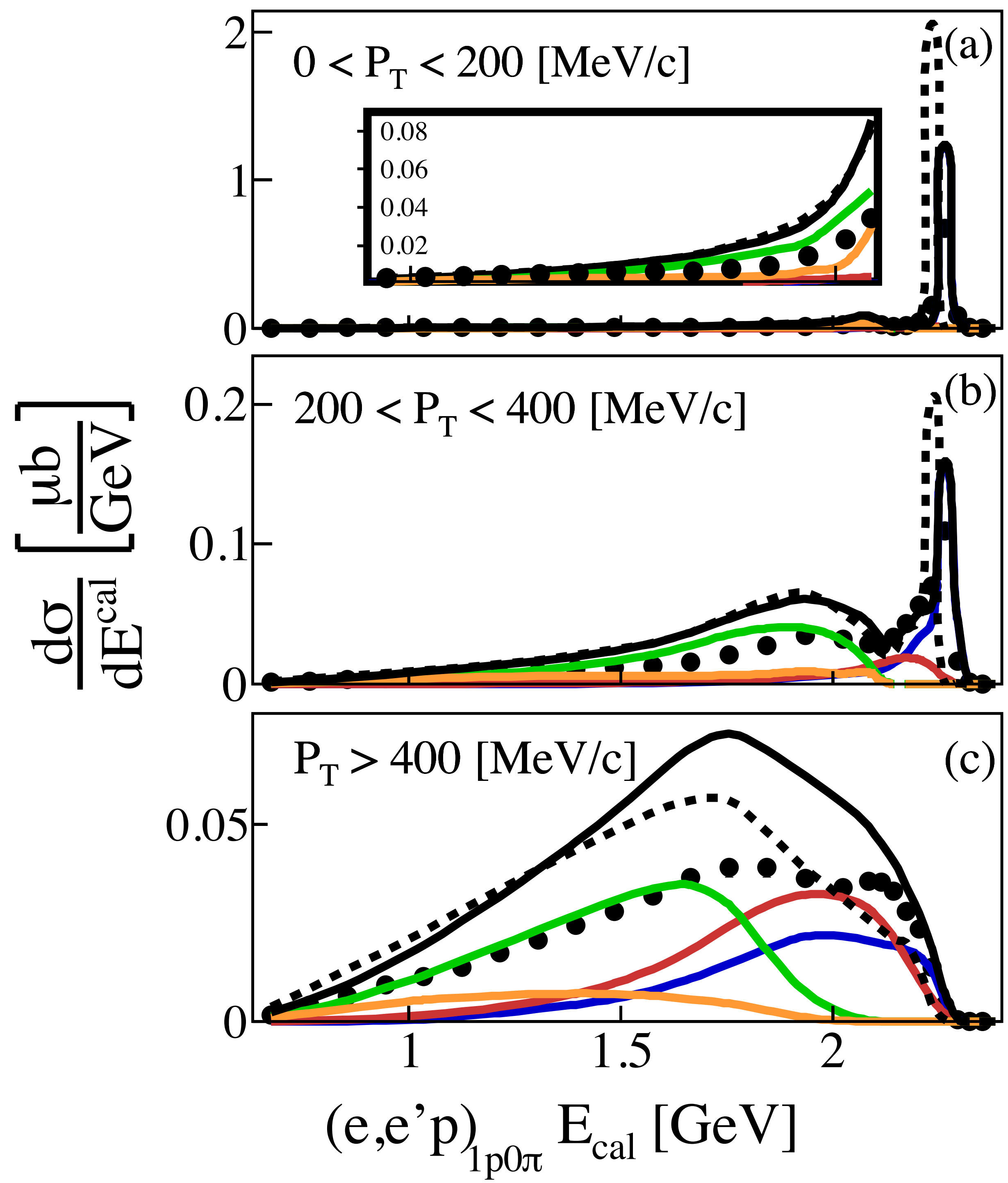
p_T sensitivity to interaction mechanisms





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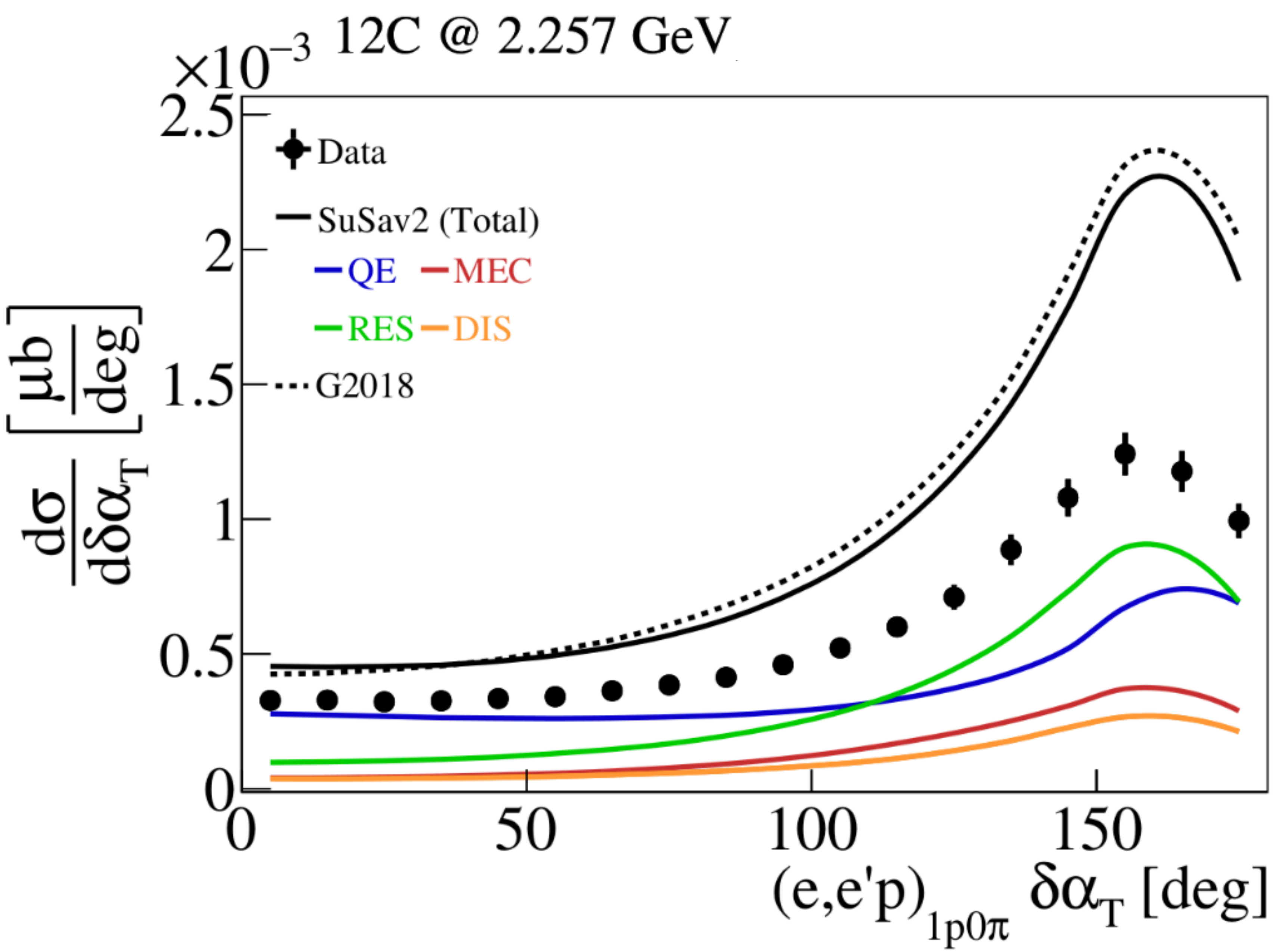
Transverse Kinematic Variables - $\delta\alpha_T$



A. Papadopoulou et al. in preparation

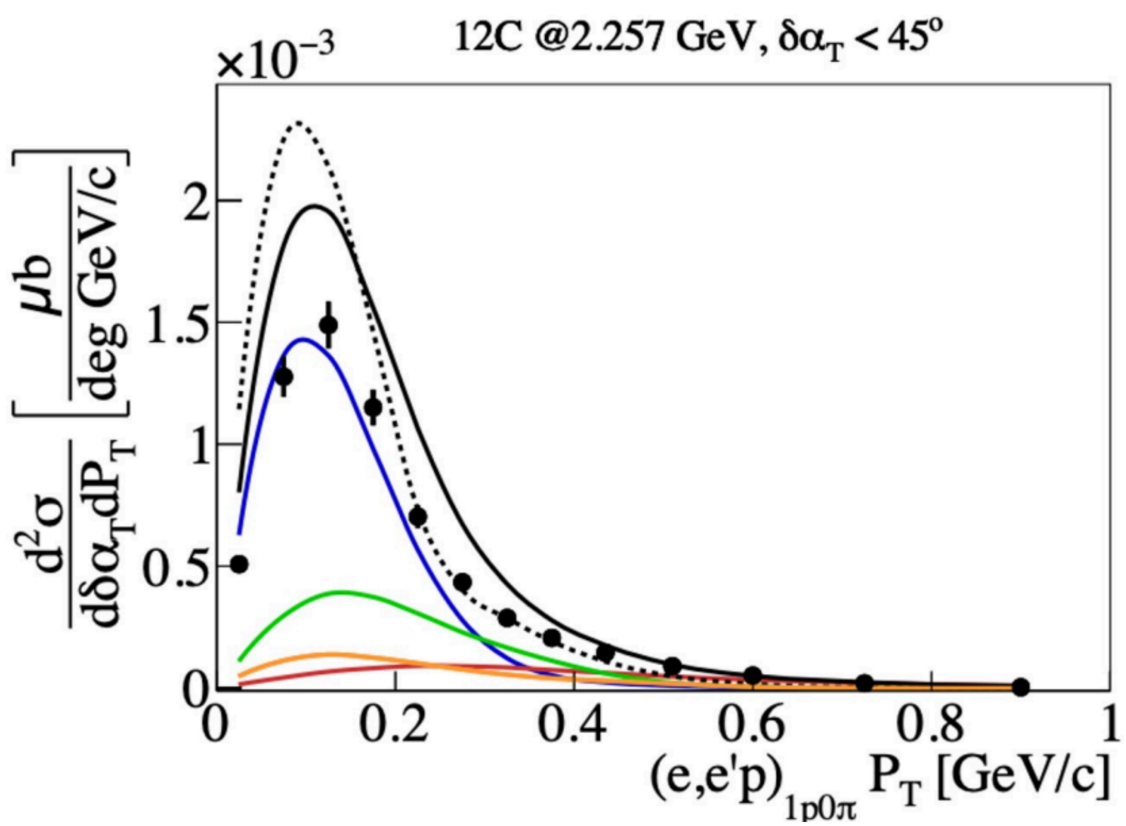
MC vs. (e,e'p) Transverse Variables

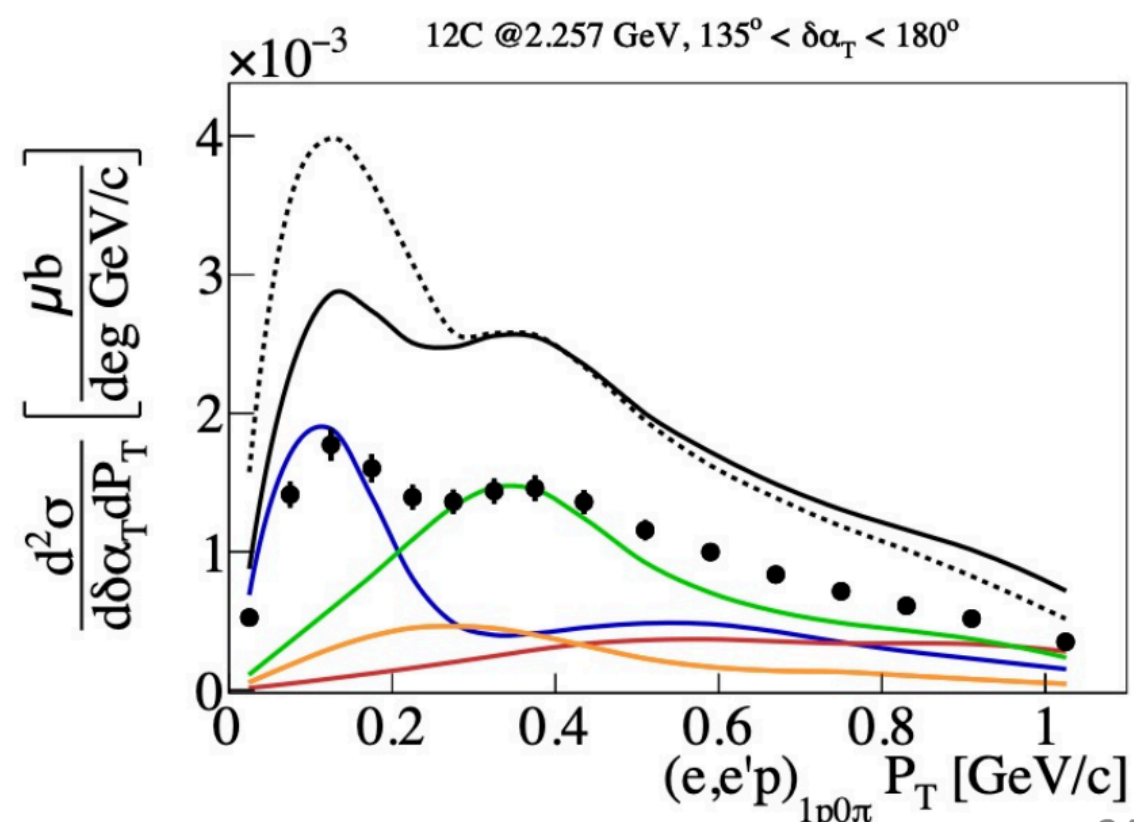
Low αT < 45

QE enhanced region

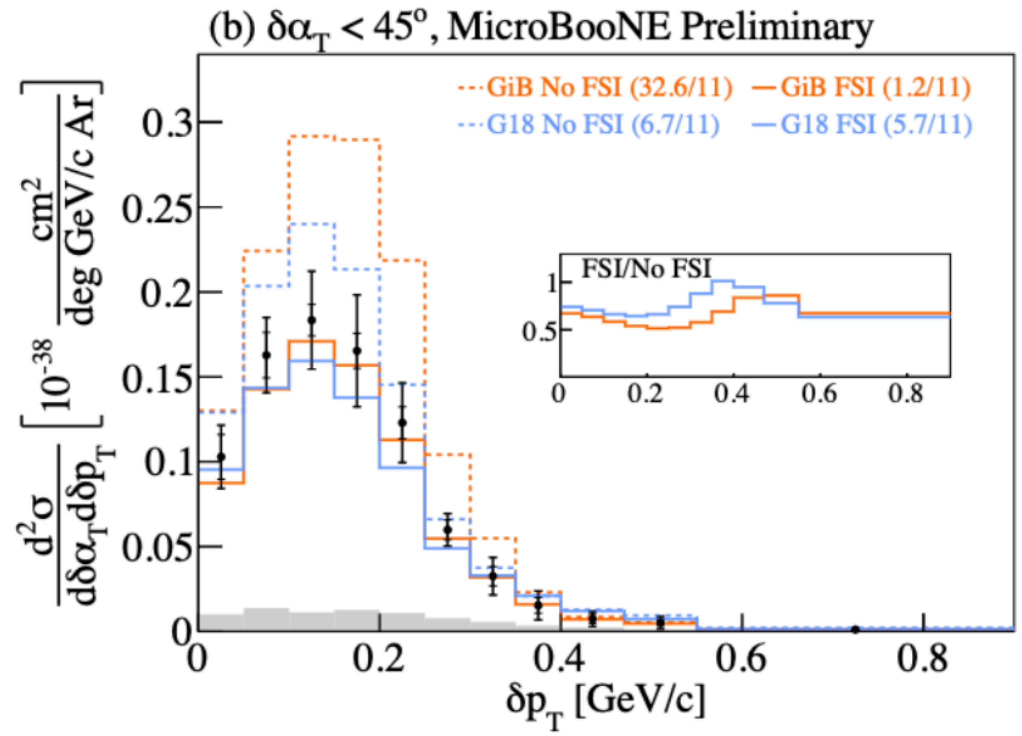
High 135 < αT < 180

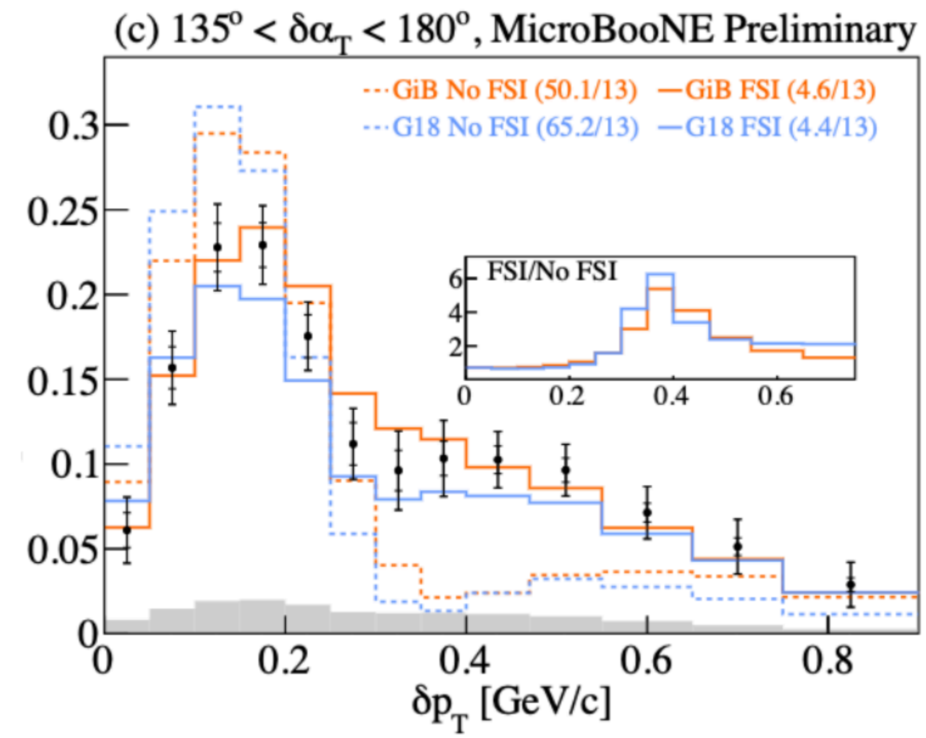
Non QE contributions

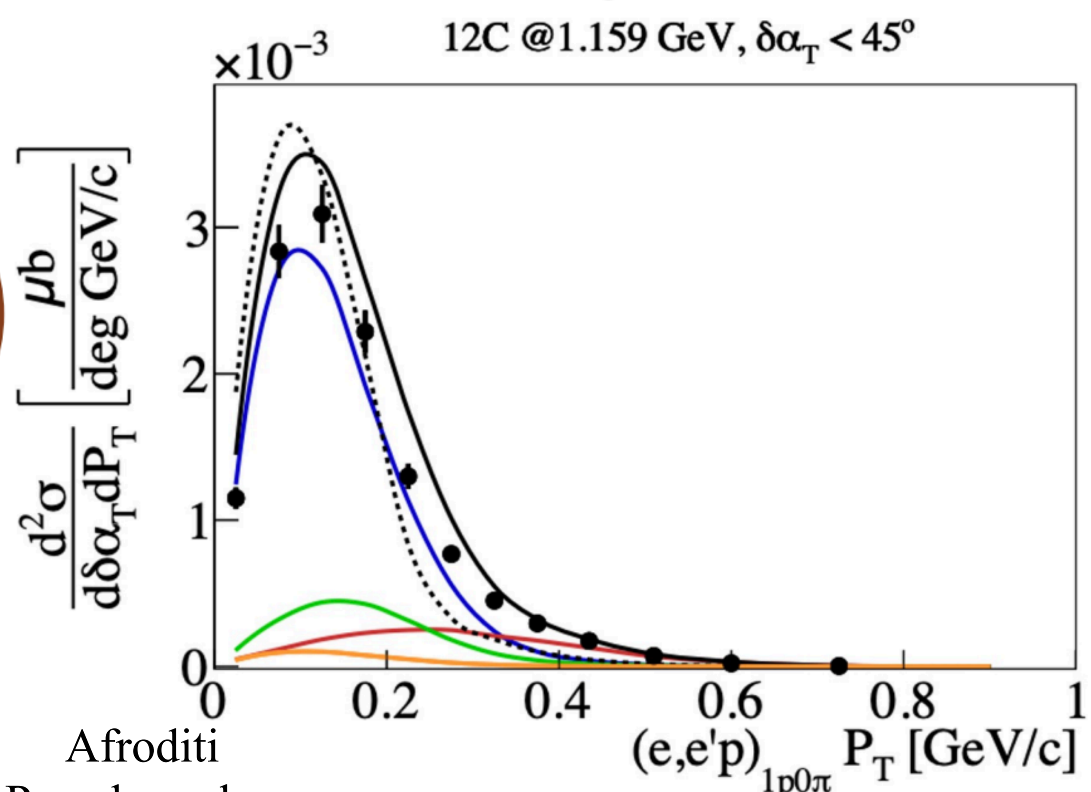


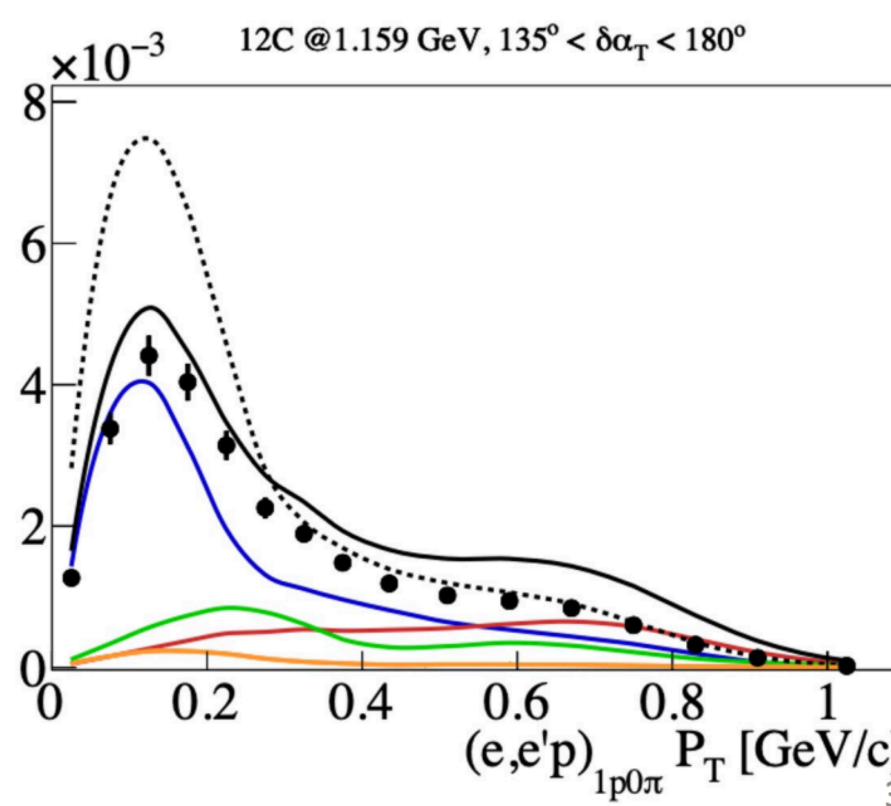


MC vs. (e,e’p) Transverse Variables









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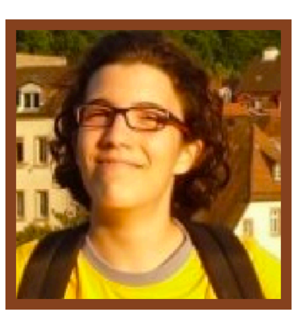


Afroditi
Papadopoulou
@ ANL

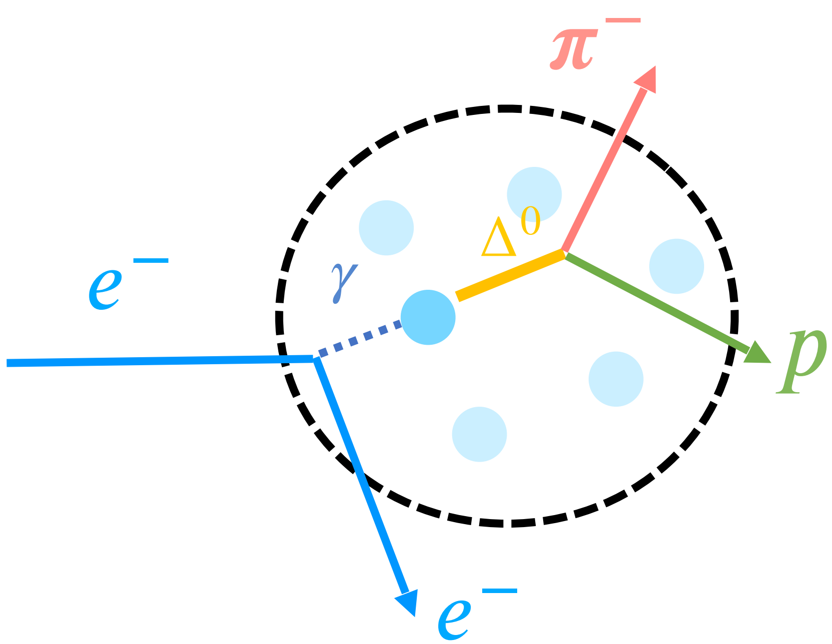
arXiv:2301.03700 [hep-ex]

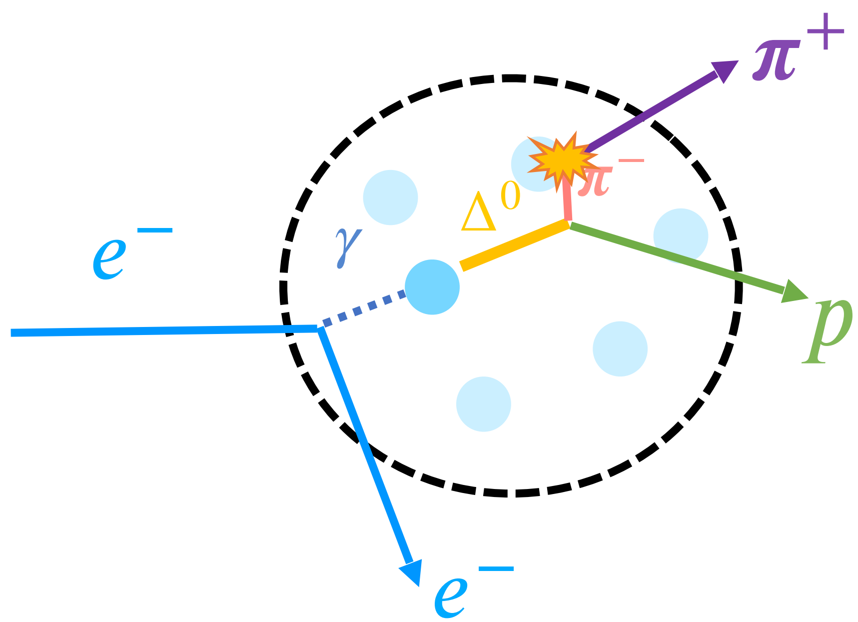
First Look at 1p1π

1p1π^- and **1p1π^+** and no other hadrons or photons

1p1π^- Possible at free nucleon level

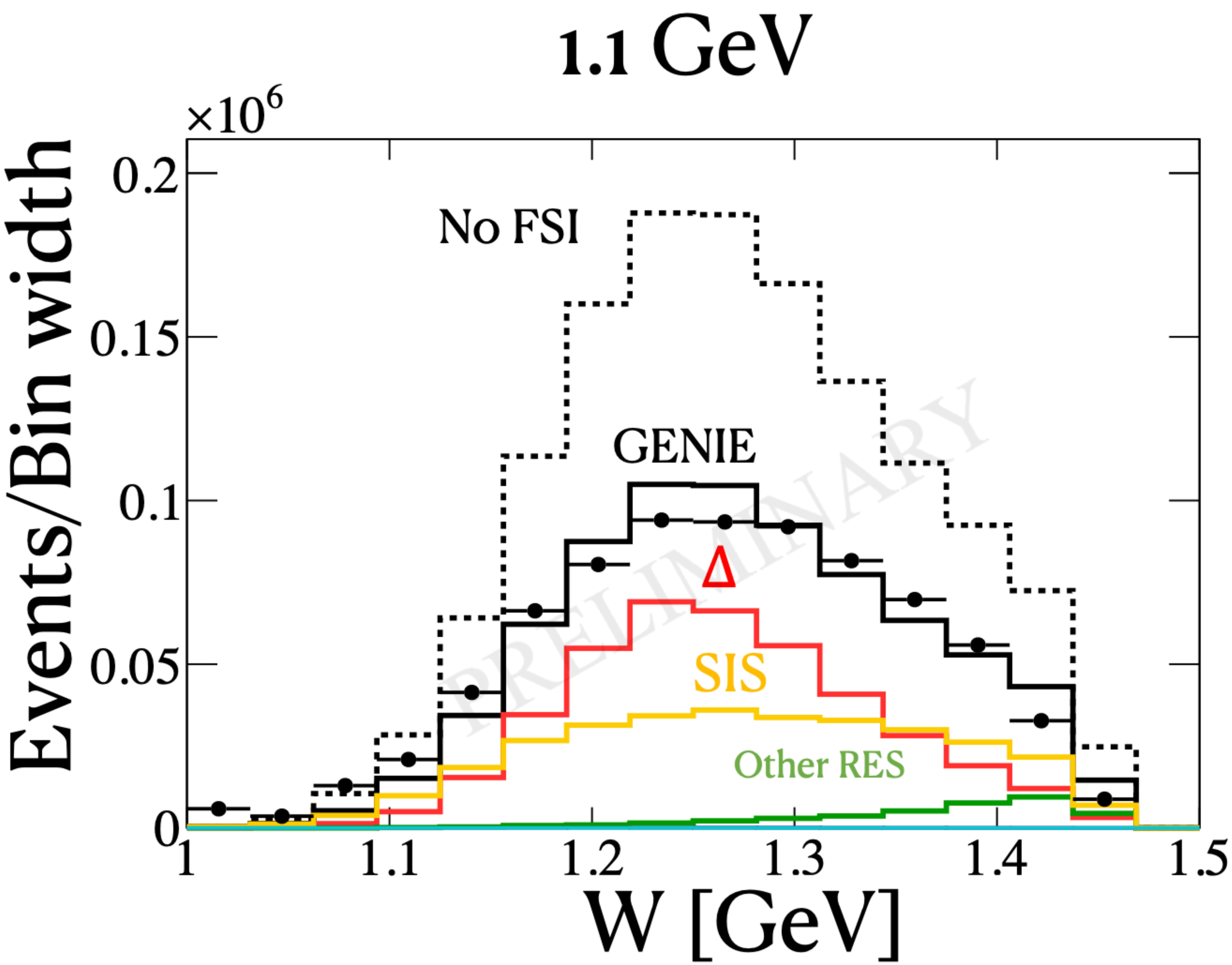
1p1π^+ needs two or more nucleons and or undetected particles (FSI)





Julia
Tena Vidal

First Look at 1p1π⁻



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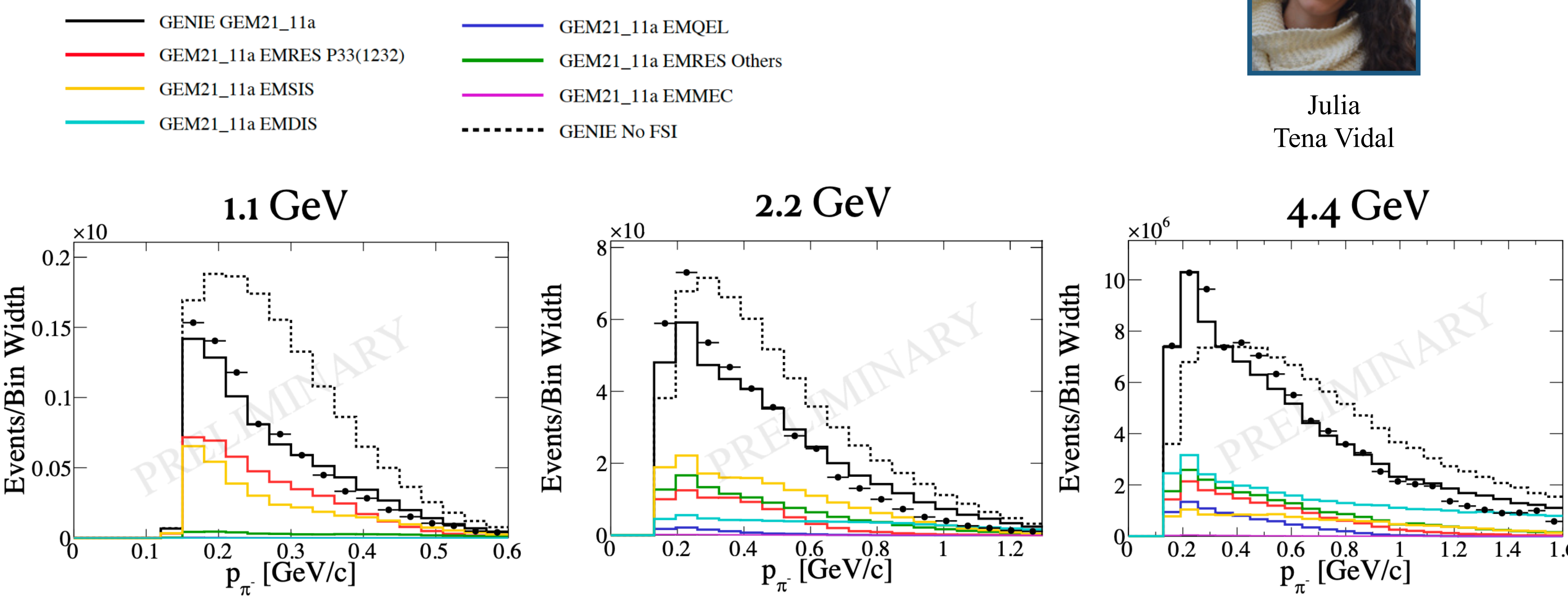
Shape-only comparison
Data corrected for bkg.
Not radiative corrected yet
Only statistical errors

First Look at 1p1π^-

Julia
Tena Vidal



Shape is well described by GENIE with FSI

First Look at 1p1π^-

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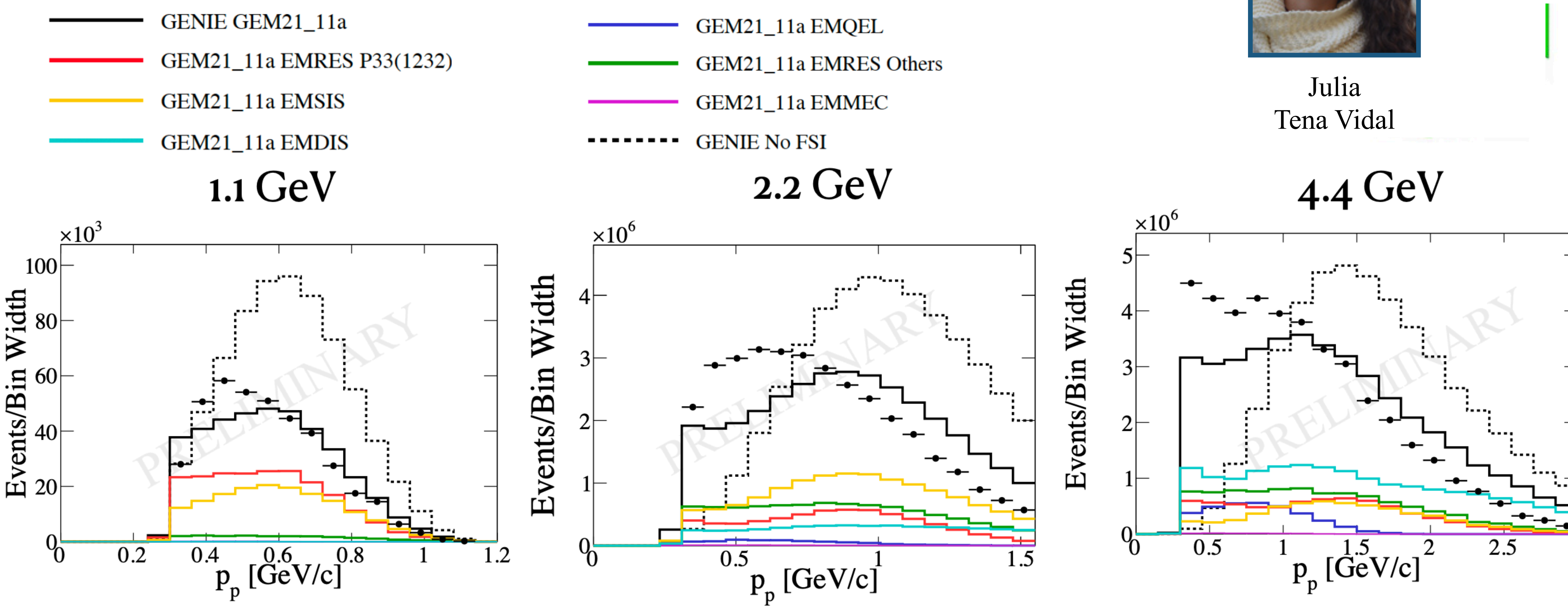
Tena Vidal

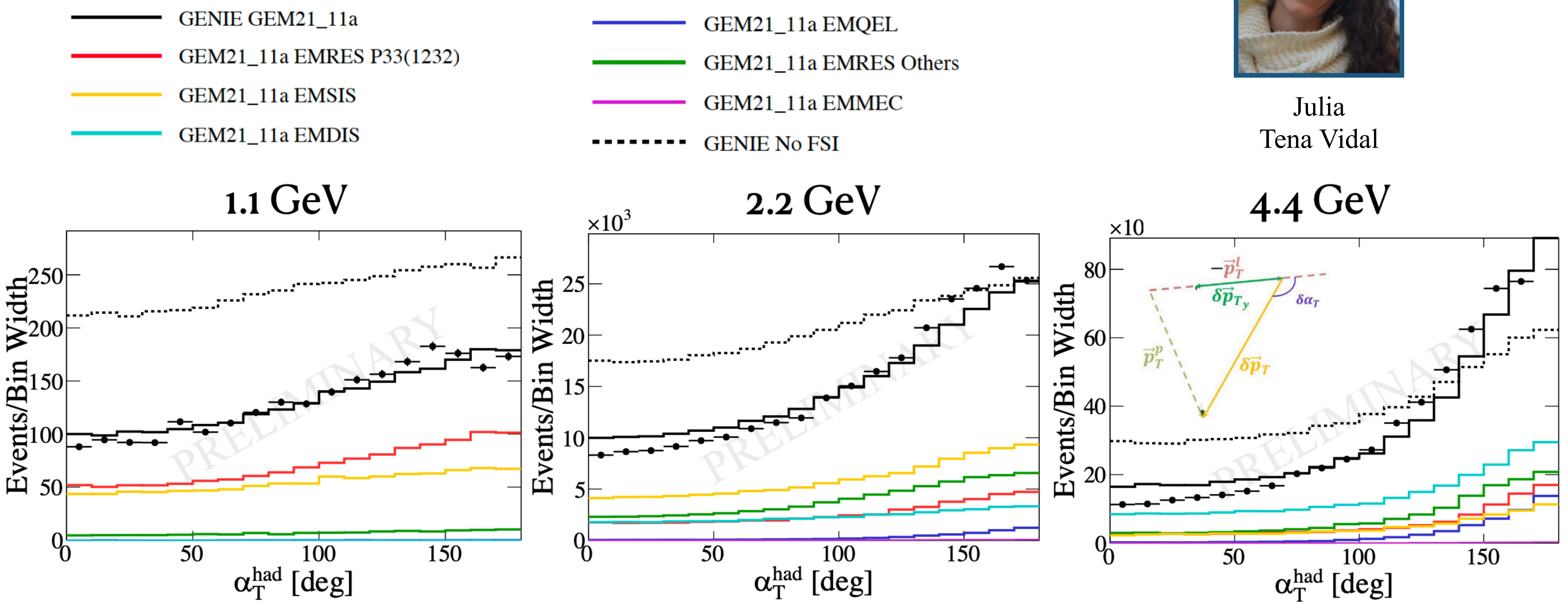


Low momentum protons are not well described

They are very sensitive to FSI

First Look at 1p1π^-

Julia
Tena Vidal

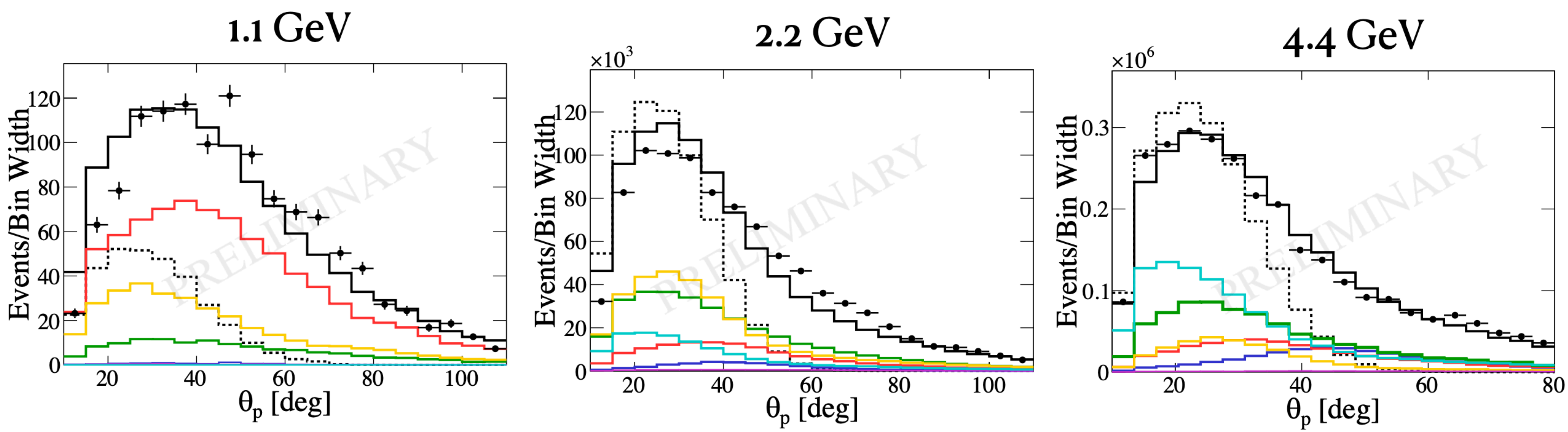


α_T most sensitive to FSI is very well described

First Look at 1p1π^+

Julia
Tena Vidal

GENIE GEM21_11a
GEM21_11a EMRES P33(1232)
GEM21_11a EMSIS
GEM21_11a EMDIS
GEM21_11a EMQEL
GEM21_11a EMRES Others
GEM21_11a EMMEC
GENIE No FSI



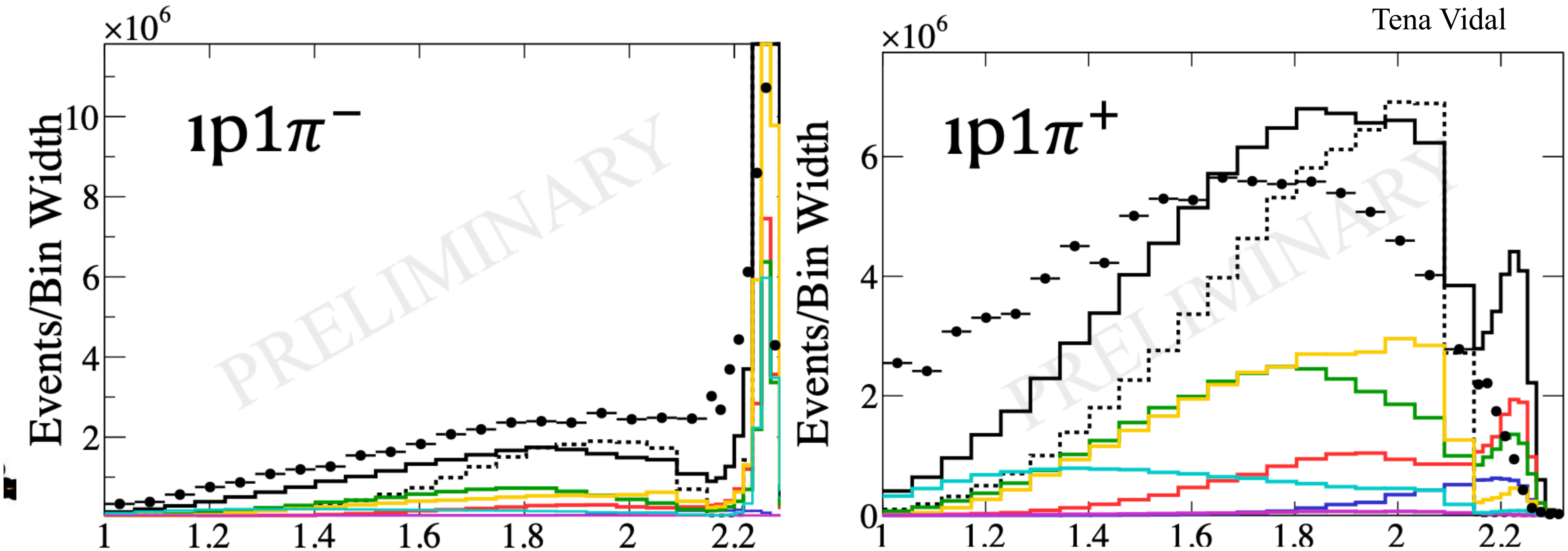
For 1p1π^+ most events are due to FSI

Well described

Reconstructed incoming energy for 1p1π

Julia
Tena Vidal

2.2 GeV on Carbon



$E_{Cal} = E_{e'} + E_{\pi} + T_p + \varepsilon_p$ $E_{Cal} = E_{e'} + E_{\pi} + T_p + \varepsilon_p$

Tail, due to missing particles, not well described

Future Plans

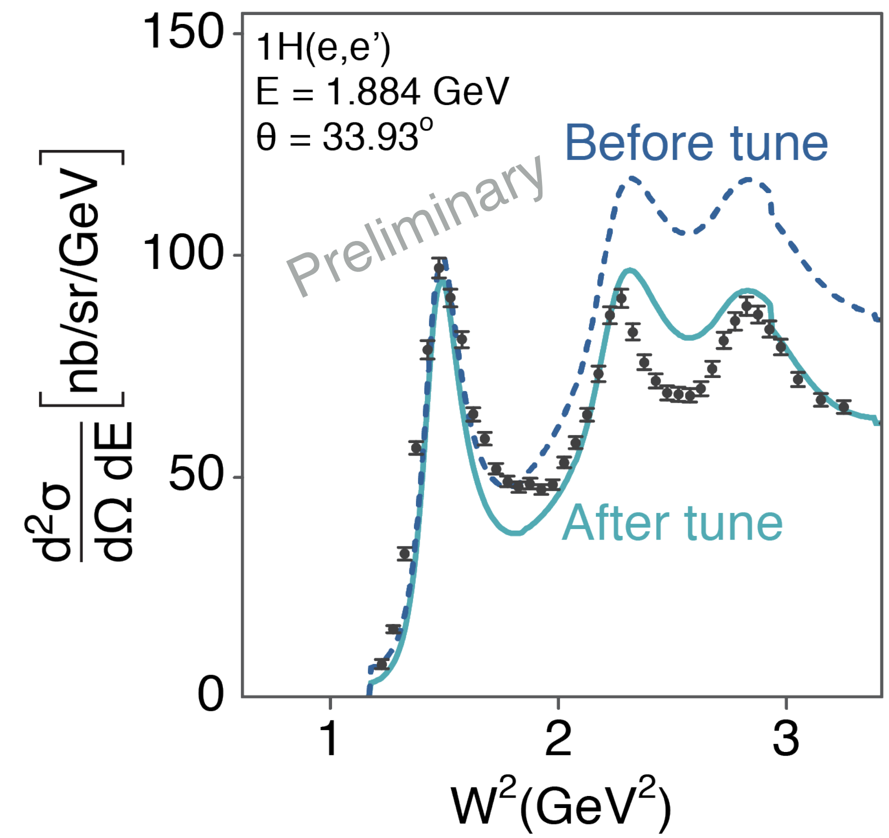
Working on:

New dataset including Argon

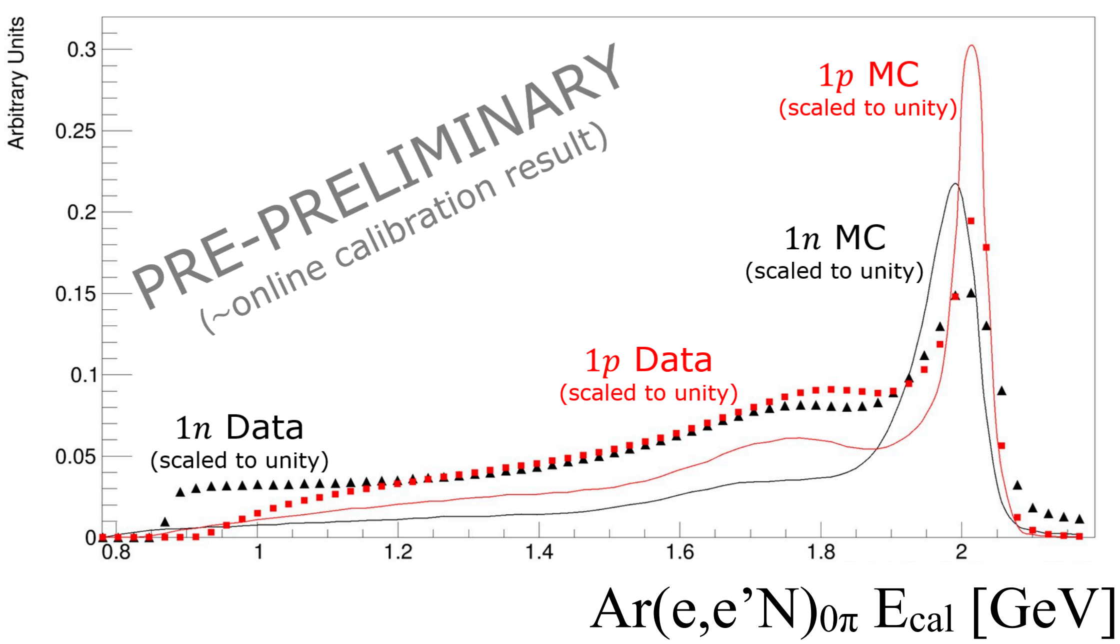
Multi differential analysis

Pion production

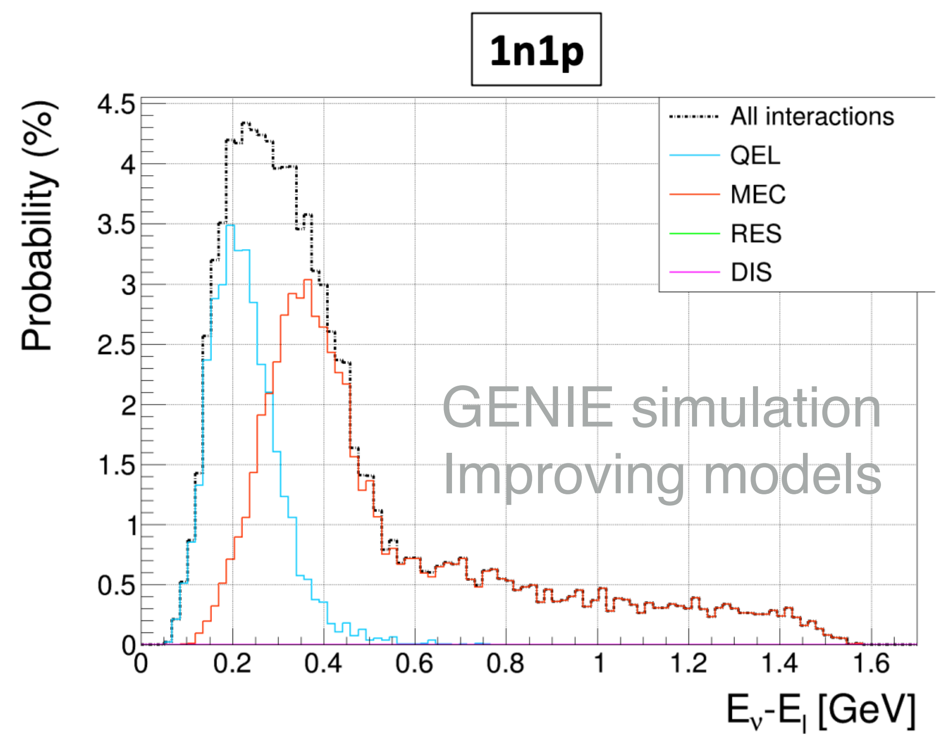
Two nucleon final state



Julia Tena Vidal



Joshua Barrow



Alon Sportes

The e4ν Collaboration

visit www.e4nu.com

Contact: Minerba betan009@fnal.gov, Adi adishka@tauex.tau.ac.il

The TAU Neutrino Group - We’re hiring

µBooNE ← local setup for neutron detection

DAQ protoDUNE

Summary

νA interaction uncertainties limit oscillation parameters extraction

While νA cross sections measured T2K, SBN

Showing first use of semi-exclusive eA data to explore νA uncertainties

Data/model disagreement even for electron QE-like events, and in the various background signatures.

Time to utilize these datasets to constrain or models and get ready for the coming exciting years

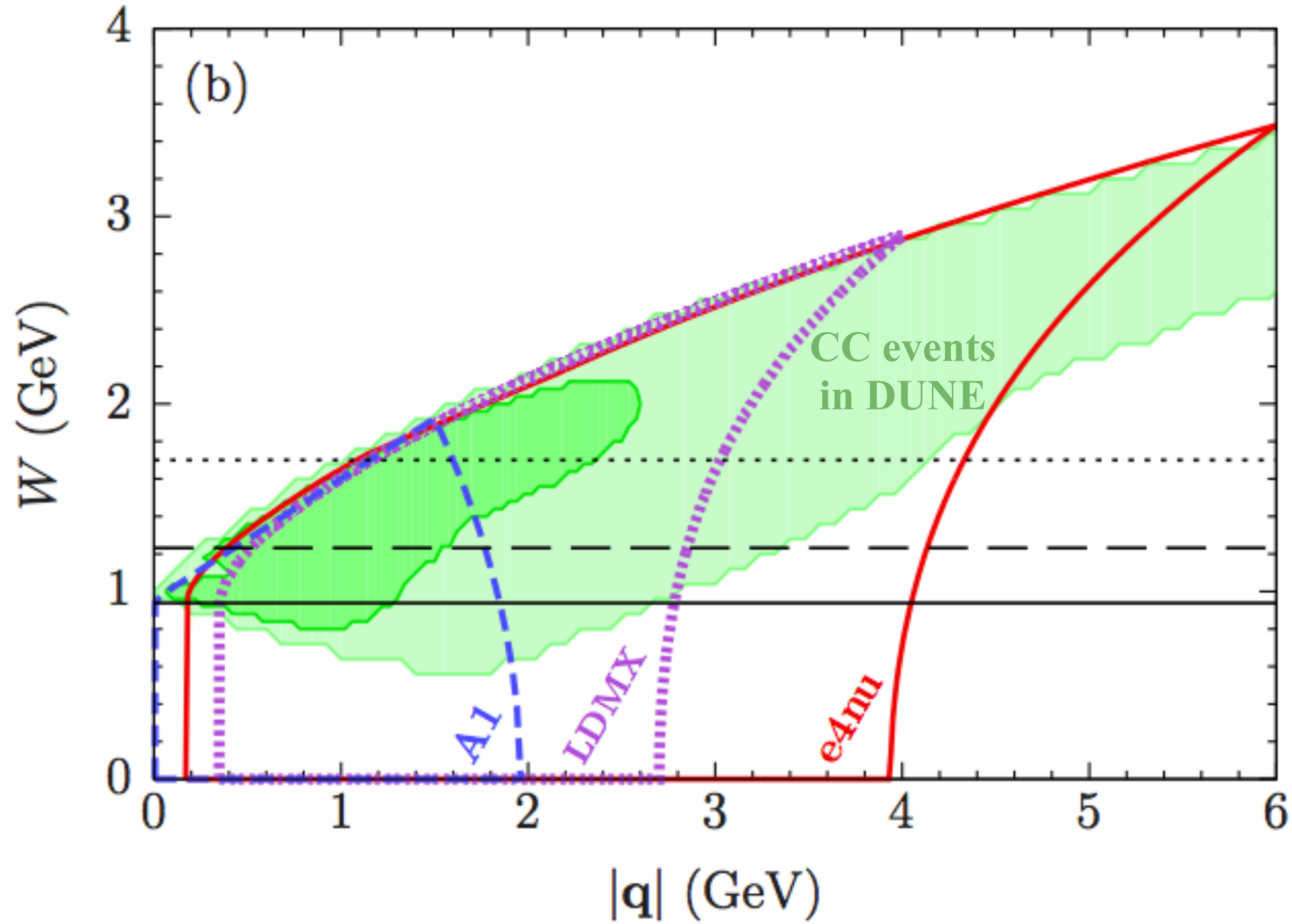
Thank you for your attention

Complementary efforts

Collaborations	Kinematics	Targets	Scattering	Publications
E12-14-012 (JLab) (Data collected: 2017) Jefferson Lab	E_e = 2.222 GeV θ_e = 15.5, 17.5, 20.0, 21.5 θ_p = -39.0, -44.0, -44.5, -47.0 -50.0	Ar, Ti Al, C	(e, e') $(e, e'p)$	Phys. Rev. C **99**, 054608 Phys.Rev.D **105** 112002
e4nu/CLAS (JLab) (Data collected: 1999, 2022) Jefferson Lab	E_e = 1, 2, 4, 6 GeV $\theta_e > 5$	H, D, He, C, Ar, ^{40}Ca, ^{48}Ca, Fe, Sn	(e, e') e, p, n, π, γ in the final state	Nature **599**, 565 Phys.Rev.D **103** 113003
A1 (MAMI) (Data collected:2020) (More data planned) mami MAINZER MIKROTRON	E_e = 1.6 GeV	H, D, He C, O, Al Ca, Ar, Xe	(e, e') 2 additional charged particles	
LDMX (SLAC) (Planned) SLAC	E_e = 4.0 GeV $\theta_e < 40$		(e, e') e, p, n, π in the final state	
eALBA (Planned) ALBA	E_e = 500 MeV - few GeV	C, CH Be, Ca	(e, e')	

Adaptation from Proceedings of the US Community Snowmass2021
arXiv:2203.06853v1 [hep-ex]

e4ν and DUNE



arXiv:2203.06853v1 [hep-ex]
A NF06 Contributed White Paper

e4ν demonstrate best coverage.

The only effort with data already taken and expected exclusive measurements.

Systematic Uncertainties - Data side

1. Background subtraction:
    1. Assuming no $\phi_{q\pi}$ dependency when rotation hadrons system around q vector. H(e, e'pπ) cross sections measured dependency affected the subtracted spectra by about 1%.
    2. Varying the CLAS φ acceptance in each sector reduced by10–20%. This changed the resulting subtracted spectra by about 1% at 1.159 and 2.257 GeV and by 4% at 4.453 GeV.
2. Varying the photon identification cuts using its velocity greater than two standard deviations (3σ at 1.159 GeV) below v = c, by ±0.25σ. This gave an uncertainty in the resulting subtracted spectra of 0.1%, 0.5% and 2% at 1.159, 2.257 and 4.453 GeV.

Systematic Uncertainties - Data side

Source	Uncertainty (%)
Detector acceptance Identification cuts $\varphi_{q\pi}$ cross section dependence Number of rotations	2,2.1,4.7 (@ 1.1,2.2,4.4 GeV)
Sector dependence	6
Acceptance correction	2-15
Overall normalization	3
Electron inefficiency	2

Modelling Consistency

Genie v3.0.6 tune G18_10a_02_11a

	electrons	neutrinos
Nuclear	Local fermi gas model	
QE	Rosenbluth CS	Nieves model
MEC	Empirical model	Nieves model
Resonances	Berger Sehgal	
DIS	AGKY	
FSI	hA2018	
Others	Radiative effects	

tune GTEST19 (SuSAv2)

	electrons	neutrinos
Nuclear	Relativistic Mean Field	
QE	SuSAv2	
MEC	SuSAv2	
Resonances	Berger Sehgal	
DIS	AGKY	
FSI	hA2018	
Others	Radiative effects	